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Original Application of Stop-Band Negative Group Delay Microwave Passive Circuit for Two-Step Stair Phase Shifter Designing

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ABSTRACT This paper investigates on the theorization, design, fabrication and measurement of original AO:3 phase shifter (PS) operating with two-step stair phase behavior. The innovative stair PS is designed with unfamiliar stop-band (SB) negative group delay (NGD) passive circuit. The elementary unfamiliar SB-NGD topology constituted by resistive, inductive, and capacitive lumped network is described. Acting as an RF and microwave circuit, the S-matrix model is expressed in function the RLC-network parameters. Thus, the canonical form of unfamiliar SB-NGD transfer function (TF) represented by the transmission coefficient is established. The unfamiliar SB-NGD circuit equations in terms of the NGD parameters are formulated. The established theory is validated comparing the calculated, simulated, and measured S-parameters and group delays (GDs). Results with a very good agreement showing unfamiliar SB-NGD behavior are observed 10 around the central frequency 2.45 GHz and bandwidth of 100 MHz. An innovative application of unfamiliar 11 SB-NGD function for the communication system front-end is developed. The developed application concept 12 of unfamiliar SB-NGD circuit is illustrated by designing a microwave device operating as a PS presenting 13 a two-step stair response completely original behavior. The basic theory, design and implementation of the 14 two-step stair PS concept are introduced. To validate the two-step stair PS principle, a proof of concept (PoC) 15 is designed based distributed element based inductive and capacitive microstrip elements. The simulated 16 and measured results of the PS PoC are in good agreement. The experimental results confirm the feasibility of two-step stair PS with phase jumping from $-70^{\circ}\pm4^{\circ}$ (from 2 GHz to 2.3 GHz) to $-104^{\circ}\pm2^{\circ}$ (from 17 18 2.6 GHz to 3.0 GHz). The investigated unfamiliar SB-NGD function-based stair PS is promising for future development 5G and 6G communication system. 19

INDEX TERMS Circuit theory, innovative concept, design method, microwave circuit, passive topology, S-20 parameter model, stop-band (SB) negative group delay (NGD), SB-NGD application, stair phase shifter (PS). 21

I. INTRODUCTION

The massive deployment of 5G technology constitutes a 23 bridging step of future wireless communication. To meet 24

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the expected users demand, innovative design of front-end RF and microwave circuit ensuring accurate performance 26 of radiation pattern is necessary [1]. This radiation perfor-27 mance is essentially ensured with improvement of beam-28 steering antenna array design [2]-[4]. Different antenna 29 array topologies as adaptive [2] and coupled phased looped

array [3] have been proposed. But these topologies need 31 to be improved to suppress the RF impairment in massive 32 antenna arrays [4]. To increase the compactness and linearity, 33 an innovative topology of metamaterial-based array antenna 34 was proposed [5], [6]. Such antenna arrays operate with linear 35 metamaterial-based phase shifters [7]. 36

The elaboration of negative refractive index (NRI) aspect 37 of metamaterial was an inspiration for the emerging RF and 38 microwave function operating with bandpass (BP) negative 39 group delay (NGD) [8], [9]. The NRI structures are also 40 known to operate with negative group velocity (NGV) effect. 41 The metamaterial BP-NGD circuits were implemented with 42 significantly lossy periodical cells [8], [9]. Therefore, RF and 43 microwave engineers wondered curiously on the existence 44 of BP-NGD circuit application. To answer, tentative applica-45 tions were suggested [10]–[24]. The BP-NGD function was 46 introduced for adaptative aspect in a microwave signal pro-47 cessing building block [10]. Then, the NGD circuit was also 48 proposed for the compensation of microwave devices [11]. 49

However, the natural NGD application is the group delay 50 (GD) equalization [12]–[14], which was proposed for the 51 microwave signal RC-network based interconnects [12], [13] 52 and also the BP filter GD rabbit ear reduction [14]. So far, the 53 most developed application of unfamiliar BP-NGD function 54 concerns the design of RF and microwave phase shifters 55 (PSs) [15]-[24]. The NGD PS was, recently, exploited to 56 develop innovative topologies of antenna array operating 57 with squint-free beamforming [15]-[21]. This type of NGD 58 antenna array application is fundamentally implemented 59 with non-Foster elements using BP-NGD networks [17], [20], [21]. Another type of innovative application was the 61 design of broadband PS using BP-NGD function operating 62 independently to the frequency [22]–[24]. 63

Further innovative work inspired from this BP-NGD PS 64 will be developed in the present paper. But before this point, 65 it would be interesting to investigate more on the unfa-66 miliar NGD function. Recent investigations from research 67 teams [25]-[32] confirm the diversity of BP-NGD topologies. 68 The BP-NGD effect was verified with absorptive filter [25] 69 and interference techniques [26]. A topology of BP-NGD 70 active circuit was implemented by using microwave transver-71 sal filter approach [27]. The complexity leads some research 72 works on the design of compact microwave passive cir-73 cuits [28], [29]. More extensive microwave function aspect as 74 the dual-band BP-NGD behavior was developed in [30]-[33]. 75 The dual-band NGD functions were also implemented with 76 compact circuits [31], [32] and with multi-coupled lines [33]. 77 Despite the progressive state of the art on the BP-NGD 78 circuit design, due to its unfamiliarity, curious questions 79 are still raised by RF and microwave design engineers 80 about the interpretation of the NGD effect. For a deep 81 illustration, an analogy between the filter theory and the 82 NGD function theory was addressed in [34]. Unlike the 83 filter, the NGD function focuses mainly on the negative sign associated to the GD response and not to the magni-85 tude response [34]-[36]. Different types of NGD function

TABLE 1.	State-of-the-art o	n the	different	types	of NGD	circuits.
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References	Туре	Passive/Active
[13, 34]	LP-NGD	Active circuit
[35-36]	LP-NGD	Passive circuit
[8-9,14, 20,25-26,28-29]	BP-NGD	Passive circuit
[10-11,13,21,27]	BP-NGD	Active circuit
[36-38]	HP-NGD	Passive circuit
[30-33]	Dual-band BP- NGD	Passive circuit
[39-40]	SB-NGD	Passive circuit

are initiated and identified [35]-[40]. The concept of lowpass (LP) NGD function was proposed in [35]. The BP-NGD [8]–[14], [20]–[29], high-pass (HP) NGD [36]–[38] and stop-band (SB) NGD [39], [40] RF passive circuits transformed from low-pass (LP) NGD cell are introduced.

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Table 1 addresses an overview on the state-of-the-art about the existing different types of NGD function which can be implemented either with passive or active circuits. It is important to note the dual-band NGD circuits as proposed in [30]–[33] are completely and ideally different to the type of SB-NGD circuits.

So far most of available research work on the design of NGD circuits can be described as follows:

- The simplest topologies are designed as LP-NGD 100 type function [13], [34]–[36]. For this type, the group 101 delay (GD) is negative from DC to certain higher frequencies.
- The BP-NGD type function containing lower and upper 104 NGD cut-off frequencies are mainly designed for RF and 105 microwave circuits [15]-[34]. 106
- By means of LP- to HP-NGD circuit transform, 107 circuit theory showing few research works was per-108 formed are available about the design of HP-NGD 109 function [36]-[38]. 110
- Then, very recent studies revealed the design feasibility 111 of the most innovative types of NGD circuits which are 112 classified as SB-NGD function [39], [40]. And deep 113 investigation can be made for this last type of NGD 114 circuit in order to develop some potential applications. 115

For this reason, the present paper investigates this SB-NGD 116 function and introduces one of its original application for 117 the design of stair phase microwave circuit. The paper is 118 organized in six sections as follows: 119

- Section II is focused on the unfamiliar SB-NGD topo-120 logical description. The theoretical approach permitting 121 the SB-NGD topological identification will be intro-122 duced. 123
- Section III develops the S-matrix model of the identified 124 SB-NGD passive cell. The analytical model in function 125 of the RLC-network parameters constituting the unfa-126 miliar SB-NGD cell will be established. The analytical 127 investigation will be followed by the elaboration of the 128 SB-NGD transfer function (TF) canonical form. 129



FIGURE 1. Two-port black box of the SB-NGD function.

- In Section IV, the SB-NGD analysis will be developed.
 Then, the synthesis design equation of circuit in function of the unfamiliar SB-NGD specifications will be formulated.
- Section V is dedicated to the discussion on the unfamiliar SB-NGD function validation results. Comparison between calculated and simulated results of a proof of concept (PoC) will be discussed.
- Section VI is the investigation on the design of stair PS prototype by using the unfamiliar SB-NGD circuit. The design principle of stair PS will be explained. An experimental validation example with a stair unfamiliar PS prototype will be treated.
- Section VII is reserved to the conclusion of the paper.

144 II. THEORETICAL INVESTIGATION ON UNFAMILIAR145 SB-NGD CIRCUIT UNDER CONSIDERATION

This section describes the SB-NGD theory. The main spec ifications of unfamiliar SB-NGD function are defined. The
 identification approach of the passive topology based on
 RLC-lumped circuit will be investigated.

150 A. ANALYTICAL DEFINITION OF SB-NGD FUNCTION

Few research work and studies [39], [40] were made so far on 151 the unfamiliar SB-NGD function. Despite the exiting results 152 available in the literature, the existence of this innovative 153 electronic function remains an open question for most of RF 154 and microwave design, fabrication and test engineers. The 155 present paragraph defines analytically the interpretation of 156 the SB-NGD function. We suppose that the two-port black 157 box microwave symmetric and passive system introduced in 158 Fig. 1 is represented analytically by the S-matrix: 159

$$[S_{NGD}(s)] = \begin{bmatrix} S_{11}(s) & S_{21}(s) \\ S_{21}(s) & S_{11}(s) \end{bmatrix}.$$
 (1)

with $s = \omega$ is the Laplace variable expressed in function of angular frequency $\omega = 2\pi f$.

We remind that the magnitude of the reflection and transmission coefficients are given by, respectively:

$$S_{11}(\omega) = |S_{11}(j\omega)| \tag{2}$$

$$S_{21}(\omega) = |S_{21}(j\omega)|.$$
 (3)

¹⁶⁷ To realize the SB-NGD analysis, the following frequency ¹⁶⁸ domain responses are essentially needed:

• the phase of the transmission coefficient which is defined by:

$$\varphi(\omega) = \arg\left[S_{21}(j\omega)\right] \tag{4}$$



FIGURE 2. (a) GD and (b) transmission coefficient responses of SB-NGD function.

• the frequency dependent GD response which is defined 172 by: 173

$$GD(\omega) = -\frac{\partial \varphi(\omega)}{\partial \omega}.$$
 (5) 174

This system is an NGD function if we can find an angular frequency, ω_x , where: 176

$$GD(\omega_x) < 0. \tag{6}$$

One of specific types associated to NGD function is the 178 SB-NGD concept. The ideal response of SB-NGD function 179 can be represented by Fig. 2(a) by taking: 180

• The cut-off angular frequencies, ω_1 and ω_2 , as roots of equation:

$$GD(\omega) = 0 \Rightarrow GD(\omega_{1,2}) = 0.$$
 (7) 18

• The transmission coefficient ideal response is represented in Fig. 2(b) by:

$$S_{21,NGD}(\omega_1 \le \omega \le \omega_2) = 1. \tag{8}$$

In Fig. 2(a) and Fig. 2(b):

- the notation BW_{NGD_L} is used to denote the lower bandwidth,
- and BW_{NGD_H} for higher bandwidth.

Because of its counterintuitive originality, most of nonspecialist electronic and RF/microwave engineers confuse the filter and NGD functions. To avoid the misinterpretation, the

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¹⁹⁴ following subsection describes the differences between these¹⁹⁵ two electronic functions.

B. SPECIFIC DIFFERENCES BETWEEN SB FILTER AND SB-NGD FUNCTION

The present analytical illustration is based on the consideration of the frequency dependent parameters associated to filter and NGD functions:

- reflection coefficient magnitudes, $S_{11filter}(f)$ and $S_{11NGD}(f)$,
- transmission coefficient magnitudes, $S_{21filter}(f)$ and $S_{21NGD}(f)$,
- and, GDs $GD_{filter}(f)$ and $GD_{NGD}(f)$.

The lower and upper cut-off frequencies in the considered frequency bands are denoted, respectively:

$$\begin{cases} f_1 = \frac{\omega_1}{2\pi} \\ f_2 = \frac{\omega_2}{2\pi} \end{cases}$$
(9)

with $f_1 < f_2$. Thus, the comparison of the SB-NGD and filter 209 behaviors and the associated specification can be made within 210 the frequency band operation bandwidth $f \in [f_1, f_2]$. In brief, 211 the main difference between the classical "stop-band" fil-212 ter and the "dual-band" NGD filter are based on which 213 parameter is used to describe it. The classical filter uses the 214 magnitude response of the transmission parameter, $|S_{21}(f)|$, 215 while, for instance, in the "stop-band NGD function", it is 216 defined by the NGD frequency band where the group delay 217 meets the condition GD(f) < 0 [34]. Different parameters 218 related to the maximum GD of the filter and the maximum 219 attenuation of NGD must be considered to characterize the 220 functions. 221

To illustrate the identification of SB NGD topology, a general analytical approach will be elaborated in the following subsection.

225 C. IDENTIFICATION APPROACH OF SB-NGD TOPOLOGY

The identification approach of SB-NGD topology can be made by the analogy with the filter [34]. Substantially, we have identified the SB-NGD passive circuit from the lowpass (LP) NGD cell based on L-inductance. The elaboration of SB-NGD cell can be made from the equivalent impedance given by:

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$$Z_a(s) = Ls. \tag{10}$$

as the reactive element. As reported in [35] and [36], the
passive cell constituted by an RL-series network mounted in
parallel behaves as a LP-NGD first-order circuit presented in
Fig. 3.

We can identify from this LP-NGD cell, the SB-NGD family by substituting the inductance L by an LC-parallel network. It yields the two-port circuit represented by the SB-NGD topology shown in Fig. 4. It acts as a second order circuit.



FIGURE 4. SB-NGD cell inspired in the family of the LP-NGD cell shown in Fig. 3.

For this case, the equivalent impedance is given by:

$$Z_b(s) = \frac{Ls}{1 + LCs^2}.$$
 (11) 24

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To analyze the identified SB-NGD cell, the S-matrix model 244 is elaborated in the following section. 245

III. S-MATRIX MODEL AND TRANSFER FUNCTION (TF) CANONICAL FORM OF THE SB-NGD TOPOLOGY

Similar to classical RF and microwave circuits, the theo-
retical analysis of the unfamiliar SB-NGD circuit will be
based on the equivalent S-matrix model. Then, the SB-NGD
canonical form will be established before the design equation248
249formulation.250

The S-matrix modelling of the SB-NGD topology under 253 study will be described in the following paragraph. 254

A. S-MATRIX MODEL OF THE SB-NGD TOPOLOGY

Let us take the terminal reference impedance, $R_0 = 50 \ \Omega$. 256 We can demonstrate analytically that the impedance matrix 257 of the SB-NGD topology shown in Fig. 3 is written as: 258

$$[Z(s)] = \begin{bmatrix} R + Z_b(s) & R + Z_b(s) \\ R + Z_b(s) & R + Z_b(s) \end{bmatrix}.$$
 (12) 25

According to the circuit and system theory, the associated ²⁶⁰ S-matrix, introduced in equation (1), can be calculated from ²⁶¹ Z-to-S transform: ²⁶²

$$[S_{NGD}(s)] = \begin{cases} \left([Z(s)] - \begin{bmatrix} R_0 & 0 \\ 0 & R_0 \end{bmatrix} \right) \times \\ \left([Z(s)] + \begin{bmatrix} R_0 & 0 \\ 0 & R_0 \end{bmatrix} \right)^{-1} \end{cases}.$$
 (13) 263

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(28)

(29)

Therefore, we establish the reflection and transmission coefficients, respectively, as:

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$$S_{11}(s) = S_{22}(s) = \frac{-R_0(1 + LCs^2)}{2R + R_0 + 2Ls + LC(2R + R_0)s^2}$$
 (14)

267
$$S_{21}(s) = S_{12}(s) = \frac{2(R + Ls + RLCs^2)}{2R + R_0 + 2Ls + LC(2R + R_0)s^2}.$$
 (15)

The corresponding SB-NGD analysis is mainly focused on the last expression as described in the next paragraph.

270 B. CANONICAL FORM OF SB-NGD TF

The TF associated to the SB-NGD topology is generally represented by the transmission coefficient:

$$T(s) = S_{21}(s).$$
 (16)

²⁷⁴ Let us denote the center angular frequency of the positive ²⁷⁵ GD (PGD) as:

$$\omega_0 = 2\pi f_0$$
 (17)

277 where:

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$$T(\omega = \omega_0) = |S_{21}(j\omega)|_{\omega = \omega_0} = 1.$$
 (18)

Then, we denote also the following NGD key parameters,GD value and the transmission coefficient, respectively:

 $\tau_n = GD(\omega_0) \tag{19}$

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$$T_n = |S_{21}(j\omega)|_{\omega=0} = S_{21}(\omega = 0).$$
(20)

²⁸³ With the real positive parameter, $T_n < 1$, the SB-NGD TF ²⁸⁴ canonical form can be expressed as:

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$$T(s) = \frac{T_n(s^2 + \omega_a s + \omega_0^2)}{s^2 + \omega_b s + \omega_0^2}$$
(21)

286 where:

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2.92

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$$\omega_a = \frac{2(1-T_n)}{T_n \tau_n} \tag{22}$$

$$_{b}=\frac{2(1-T_{n})}{\tau_{n}}.$$
(23)

By identification with the transmission coefficient expressedin equation (15), we have:

(n)

$$T_n = \frac{2R}{2R + R_0} \tag{24}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{25}$$

$$\tau_n = R_0 C = \frac{R_0}{L\omega_n^2} > 0. \tag{26}$$

²⁹⁴ In this case, the reflection coefficient proposed in equa-²⁹⁵ tion (14) can then be rewritten as:

296
$$S_{11}(s) = \frac{(T_n - 1)(s^2 + \omega_0^2)}{s^2 + \omega_b s + \omega_0^2}.$$
 (27)

²⁹⁷ Knowing the S-matrix model, the frequency responses will²⁹⁸ be analyzed in the following subsection.

used on 1. $T(\omega) = \frac{\sqrt{(T_n \tau_n)^2 (\omega^2 - \omega_0^2)^2 + 4(\omega - T_n \omega_0)^2}}{\sqrt{\tau_n^2 (\omega^2 - \omega_0^2)^2 + 4(\omega - T_n \omega_0)^2}}.$

respectively, by:

The transmission phase yielded from the transmission coefficient is expressed as: 300

C. ANALYSIS OF S-PARAMETER FREQUENCY RESPONSES

The magnitudes of the reflection and transmission coeffi-

cients, $S_{11}(\omega) = |S_{11}(j\omega)|$ and $T(\omega) = |T(j\omega)|$ are given,

 $S_{11}(\omega) = \frac{\left| (1 - T_n)(\omega^2 - \omega_0^2) \right|}{\sqrt{\tau_n^2 (\omega^2 - \omega_0^2)^2 + 4(\omega - T_n \omega_0)^2}}$

$$\varphi(\omega) = \varphi_{\varpi}(\omega) - \varphi_{\vartheta}(\omega) \tag{30}$$

with:

$$\varphi_{\overline{\omega}}(\omega) = \arctan\left[\frac{2(T_n - 1)\omega}{T_n\tau_n(\omega^2 - \omega_0^2)}\right]$$
(31) 30

and:

$$\rho_{\vartheta}(\omega) = \arctan\left[\frac{2(1-T_n)\omega}{\tau_n(\omega^2 - \omega_0^2)}\right].$$
 (32) 31

The SB-NGD analysis can be explored from these expressions.

IV. SB-NGD ANALYSIS AND SYNTHESIS OF THE IDENTIFIED RLC-NETWORK BASED TOPOLOGY

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The NGD analysis consists in the identification of the NGD existence condition written in equation (6), in the appropriated frequency bands. The NGD condition can be transformed into a relation between the elements of the topology under study by considering the GD expressed in equation (5). Subsequently, to explore this condition, we need to start with the GD expression versus frequency. 320

A. FREQUENCY DEPENDENT EXPRESSION OF GD

The GD defined in equation (5), which takes into account the ³²⁴ transmission phase written in equation (30), is expressed as: ³²⁵

$$GD(\omega) = GD_{\vartheta}(\omega) - GD_{\overline{\omega}}(\omega) \tag{33}$$

or

$$GD(\omega) = \frac{\partial \varphi_{\vartheta}(\omega)}{\partial \omega} - \frac{\partial \varphi_{\varpi}(\omega)}{\partial \omega}$$
(34) 328

with

$$GD_{\varpi}(\omega) = \frac{2\tau_n(1-T_n)(\omega^2+\omega_0^2)}{\tau_n^2(\omega^4+\omega_0^4)+2\left[2(1-T_n)^2-\tau_n^2\omega_0^2\right]\omega^2} \quad (35)$$

$$GD_{\vartheta}(\omega) = \frac{2\tau_n T_n (T_n - 1)(\omega^2 + \omega_0^2)}{T_n^2 \tau_n^2 (\omega^4 + \omega_0^4) + 2\left[2(1 - T_n)^2 - T_n^2 \tau_n^2 \omega_0^2\right] \omega^2}$$
(36)

The exploration of this GD constitutes the SB-NGD analysis 333 and synthesis to be developed in the next subsection. 334



FIGURE 5. Product κ versus (f_n, T_n) with f_n (a) from 0.5 to 1.5 GHz and (b) from 1.5 GHz to 5 GHz.

335 **B.** ANALYSIS AT VERY LOW FREQUENCIES ($\omega \approx 0$)

We recall that at very low frequencies, $\omega \approx 0$, the reflection and transmission coefficients of equations (28) and (29) become:

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$$\begin{cases} S_{11}(\omega = 0) = 1 - T_n \\ S_{21}(\omega = 0) = T_n \end{cases}$$
(37)

At the same frequency, the GD introduced in equation (31) is simplified as:

$$GD(\omega \approx 0) = \frac{-2(1-T_n)^2}{T_n \tau_n \omega_0^2} < 0.$$
 (38)

³⁴³ For the interpretation of this relation, the mapping of the ³⁴⁴ product:

$$\kappa = GD(f \approx 0) \times GD(f \approx f_0) \tag{39}$$

³⁴⁶ versus (f_0, T_n) varied from (0.5 GHz, -10 dB) to (5 GHz, ³⁴⁷ -1 dB) is presented in Figs. 5. It can be seen that the product κ ³⁴⁸ is inversely proportional to f_n and T_n . As an interesting remark ³⁴⁹ inferred from the plot of Figs. 5:

- when f_n increases from 0.5 GHz to 1.5 GHz, the product, κ , decreases from about -0.3 ns² to -299 ps²,
- and when the characteristic frequency varies from 1.5 GHz to 5 GHz, the product, κ , decreases from -0.03 ns² to -26.9 ps².

355 C. EXPRESSION OF SB-NGD BANDWIDTH

We can remark that the GD established in equation (38) is always negative for any values of parameters in the topology proposed in Fig. 4. Moreover, the NGD cut-off frequencies can be determined as the roots of equation (7) by using the GD given in (33). Consequently, we find the cut-off frequencies given by:

$$\omega_1 = \frac{\sqrt{2(T_n - 1)^2 + T_n(\tau_n \omega_0)^2 + 2\zeta(1 - T_n)}}{\tau_{rr}/T_r} \quad (40) \quad {}_{36}$$

$$_{2} = \frac{\sqrt{2(T_{n}-1)^{2} + T_{n}(\tau_{n}\omega_{0})^{2} - 2\zeta(1-T_{n})}}{\tau_{n}\sqrt{T_{n}}} \quad (41) \quad {}_{36}$$

where:

(I)

$$\zeta = \sqrt{(T_n - 1)^2 + T_n(\tau_n \omega_0)^2}.$$
 (42) 36

The bandwidth with positive GD (PGD) can be calculated with the relation: 367

$$BW = \omega_2 - \omega_1. \tag{43}$$

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D. PROPERTIES OF SB-NGD FUNCTION

Similar to the cases of the most developed types of NGD function as LP-NGD and BP-NGD ones, the SB-NGD function presents some specific analytical properties. It is interesting to note that the cut-off frequencies and PGD center frequency are linked by the equation: 374

$$\frac{\omega_2 \omega_1}{\omega_0^2} = 1. \tag{44}$$

In addition to this relationship, we remind also that:

- At the central frequency According to equation (18), the magnitude $T(\omega = \omega_0) = 1$ and the GD at the is equal to $GD(\omega_0) = \tau_n > 0.$
- At very low frequency, the magnitude as given in equation (35) must be $T(\omega \approx 0) < 1$ and the GD at very low frequency $GD(\omega \approx 0) < 0$.

In brief, the passive circuit introduced in Fig. 4 enables to have: 383

$$\begin{cases} GD(\omega < \omega_1) < 0\\ GD(\omega_1 < \omega < \omega_2) > 0\\ GD(\omega > \omega_2) < 0 \end{cases}$$
(45) 38

This statement confirms that the circuit introduced in Fig. 4 ³⁸⁶ behaves as a SB-NGD function. ³⁸⁷

E. SYNTHESIS AND DESIGN EQUATIONS OF SB-NGD CIRCUIT

The design of the SB-NGD circuit must start with the specifications of: 391

- The PGD center frequency, τ_n , 392
- The attenuation at very low frequency, T_n ,
- The expected PGD, τ_n , which is linked with the NGD ³⁹⁴ at very low frequency, $\tau_0 = GD_0 < 0$, given in ³⁹⁵ equation (36). ³⁹⁶

Therefore, the equations of the SB-NGD circuit R, L, and C 397 parameters are given by: 398

$$R = \frac{T_n R_0}{2(1 - T_n)}$$
(46) 399

$$L = \frac{R_0}{\tau_n \omega_0^2}$$
(47) 400



FIGURE 6. Variations of SB-NGD circuit parameters: (a) R, (b) L, and (c) C, versus (T_n, τ_n) .

TABLE 2. Minimum and maximum values of synthesized *R*, *L* and *C* parameters.

Parameters	T_n	$ au_n$	R	L	С
Min.	-10 dB	0.1 ns	23.1 Ω	5.1 pH	2 pF
Max.	-1 dB	10 ns	410 Ω	50.7 nH	0.2 nF

401

We can remind that T_n must verify the condition, $0 < T_n < 1$. The different ranges of R, L, and C values versus (T_n, τ_n) are plotted in Figs. 6. According to these graphical plots, it can be seen that:

- *R* increases with T_n , *L* varies inversely proportional to T_n and τ_n , and *C* increases proportionally to τ_n .
- The *R*-variation slope is particularly weak, lower than 10 Ω/dB , when T_n is below -6 dB, against the slope above -4 dB, which is more than 100 Ω/dB .
- The *C*-variation presents a slope less than 10 pF/decade when τ_n is lower than 1 ns against more than 100 pF/decade when τ_n is higher than 1 ns.

⁴¹⁴ Table 2 summarizes the minimal and maximal values of *R*, *L*, ⁴¹⁵ and *C* versus the considered minimal and maximal range of ⁴¹⁶ (T_n, τ_n) .

To verify the feasibility of the developed SB-NGD theory, PoC practical investigation will be presented in the next section.

420 V. VERIFICATION RESULTS WITH PROOF OF

421 CONCEPT (POC) CIRCUIT OF SB-NGD TOPOLOGY

The present section deals with the validations of the SB-NGD topology. After the PoC description, parametric simulations are described in order to quantify the influence of the R,



FIGURE 7. Schematic of the simulated SB-NGD circuit PoC.

TABLE 3. Parameters of the SB-NGD circuit PoC.

Description	Parameter	Ideal value
	Center frequency	$f_0=2.45~{ m GHz}$
Specifications	BW	$BW_{PGD}=0.3 \text{ GHz}$
specifications	NGD value	$\tau_n = -0.1 \text{ ns}$
	Attenuation	$T_0 = -3 \text{ dB}$
	Resistor	<i>R</i> =61 Ω
calculated NGD	Inductor	<i>L</i> =0.5 nH
circuit parameters	Capacitor	<i>C</i> =8.35 pF

L, and C component parameters on the NGD behavior. The overall validation aspects are originally focused on analyzing NGD function. 427

A. POC DESIGN DESCRIPTION

(48)

The SB-NGD circuit design was performed with the appli-429 cation of synthesis equations of R, L, and C expressed in 430 equations (46), (47), and (48), respectively. Fig. 7 shows 431 the design of the SB-NGD schematic circuit in the environ-432 ment of the electronic and RF/microwave circuit simulator 433 ADS(R) from Keysight Technologies. The NGD specifica-434 tions and designed circuit electrical parameters are indicated 435 in Table 3. 436

To illustrate the robustness of the SB-NGD behavior, sensitivity analysis with respect to the circuit parameters will be discussed in the following subsection. 439

B. SB-NGD RESPONSE SENSITIVITY ANALYSIS

Sensitivity analyses with respect to the resistor, R+/-5%, 441 inductor, L+/-5%, and capacitor, C+/-5%, have been 442 conducted for the robustness of the SB-NGD circuit. 443 The sensitivity analyses enable to explain more explicitly 444 the circuit parameter effects onto the SB-NGD function. The 445 MATLAB® calculations of GD, S_{11} , and S_{21} introduced 446 in equation (33), equation (28), and equation (29) to be 447 discussed in the following paragraphs with the S-parameter 448 analytical expressions, are carried out from 2 GHz 449 to 3 GHz. 450

428



1) SENSITIVITY ANALYSIS VERSUS R 451

The effect of resistor, R, was investigated under linear vari-452 ations from 58 Ω to 64 Ω with τ fixed values of L and C. 453 The calculated results are represented as cartographies with 454 color scale variation of responses in function of couple (f_0, R) . 455 Fig. 8(a), Fig. 8(b), and Fig. 8(c) display the results of the 456 calculations of GD, S_{11} , and S_{21} , respectively. The SB-NGD 457 behavior is occurred for all the value of the considered range 458 of R. It is noteworthy that the specified parameters, center 459 frequency, $f_0 = 2.458$ GHz, $GD(f_0) = 0.42$ ns, $S_{11}(f_0) =$ 460 -38 dB, and $S_{21}(f_0) = -4 \text{ mdB}$ are less sensitive to variation 461 of *R*. 462

2) SENSITIVITY ANALYSIS VERSUS L 463

The inductor variation effect was investigated via linear sen-464 sitivity analysis of inductor L varied from 4.75 nH to 5.25 nH 465 with fixed resistor and capacitor during the S-parameter 466 calculations. Fig. 9(a), Fig. 9(b), and Fig. 9(c) display the 467 corresponding results. 468

It can be seen with the three cartographies that the NGD 469 center frequency increases with L. More rigorous analysis can 470 be done from observation of f_0 , $GD(f_0)$, $S_{11}(f_0)$, and $S_{21}(f_0)$ 471 variations plotted in Figs. 10(a), Fig. 10(b), and Fig. 10(c), 472 respectively. 473

3) SENSITIVITY ANALYSIS VERSUS C 474

This paragraph presents the capacitor variation effect onto the 475 SB-NGD circuit responses. 476

The analysis is performed with linear sensitivity analysis of 477 capacitor C varied from 7.93 pF to 8.77 pF with fixed resistor 478 and inductor during the S-parameter calculations. Fig. 11(a), 479 Fig. 11(b), and Fig. 11(c) display the corresponding results. 480 It can be seen with the three cartographies that the NGD 481





FIGURE 10. GD(f_0), f_0 , $S_{11}(f_0)$, and $S_{21}(f_0)$ versus L.

center frequency increases with C. More rigorous observation 482 of f_0 increasing from 2.4 GHz to 2.525 GHz, $GD(f_0)$, $S_{11}(f_0)$, 483 and $S_{21}(f_0)$ variations are plotted in Fig. 12(a), Fig. 12(b), and 484 Fig. 12(c), respectively. 485

C. DISCUSSION ON CALCULATED AND SIMULATED **SB-NGD RESULTS**

The PoC of SB-NGD circuit was simulated from 2 GHz 488 to 3 GHz. Comparisons between the calculated ("Calc.") and 489 simulated ("Simu.") with ADS® results are displayed in 490

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FIGURE 11. Parametric results versus C: (a) GD, (b) S₁₁, and (c) S₂₁.



FIGURE 12. $GD(f_0)$, f_0 , $S_{11}(f_0)$, and $S_{21}(f_0)$ versus C.

Fig. 13. The calculated results were obtained with a program developed in Matlab using S-parameters equations. It can be pointed out that these comparative results present a very good agreement. As expected, and seen in Fig. 13(a), in the working frequency band, the considered circuit PoC presents a SB-NGD behavior around center frequency of approximately $f_0 = 2.46$ GHz.



FIGURE 13. Comparisons of calculated and simulated (a) GD and (b) transmission parameters from the SB-NGD PoC shown in Fig. 8.

Approach	f _o (GHz)	$\tau(f_o)$ (ns)	BW (MHz)	$S_{21}(f_o)$ (dB)	$S_{11}(f_o)$ (dB)
Calculated	2.46	4.17	267	-0.42	-17
Simulated	2.46	4.16	268	-0.41	-18

TABLE 4. Comparison of calculated and simulated SB-NGD prototype parameters.

TABLE 5.	Comparison of SB NGD circuit specifications with the
state-of-t	he-art.

Approach	f_o	$ au(f_o)$	BW	Attenuation @ fo
[36]	0.5 GHz	2 ns	46 MHz	-0.05 dB
[39]	32 MHz	0.89 ns	83.6 MHz	-7.3 dB
[40]	0.95 kHz	108 µs	1.45 kHz	-4.08 dB
This work	2.46 GHz	4.16 ns	268 MHz	-0.41 dB

Table 4 summarizes the differences between the calculated and simulated NGD parameters.

After the SB-NGD sensitivity analysis and feasibility 500 study, an original case of application to design a stair PS for 501 microwave system will be explored in the following section. 502

D. COMPARISON OF SB NGD SPECIFICATIONS

The present subsection proposes a state-of-the-art investiga-504 tion about the unfamiliar SB NGD function. We can compare 505 the specifications of the considered NGD circuit with the very 506 few research works available in the literature about the SB 507 NGD circuit design [36], [39], [40]. Table 5 summarizes the 508 comparison of NGD at center frequency f_o , GD $\tau(f_o)$ at the 509 center frequency, bandwidth BW and also the attenuation at 510 center frequency. 511

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FIGURE 14. Two-port black box of positive group delay (PGD) circuit.

The present research work is particularly challenging with the possibility of SB-NGD circuit design operating at higher central frequency with very low attenuation loss.

At this stage, we may wonder about the designability of SB NGD integrating into a PS. The following section develops the innovative stair PS design, fabrication and test of the proof of concept.

519 VI. SB-NGD CIRCUIT BASED-STAIR PS DESIGN,

520 FABRICATION AND TEST

As original application of the previously investigated
 SB-NGD circuit, we can design an innovative stair PS never
 been done before. The next paragraph introduces the principle
 of the stair PS.

525 A. THEORETICAL APPROACH OF STAIR PS DESIGNING

The present subsection describes the theoretical approach of SB-NGD function application for stair PS circuit design. The design is illustrated by graphical diagram representation based on the S-matrix operation.

530 1) DESIGN PRINCIPLE OF STAIR PS WITH SB-NGD

531 FUNCTION

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For the basic understanding, we consider the case of twostep stair PS in the present study. Thus, we assume that the frequency band of interest is written as:

$$BW_L = \begin{bmatrix} \omega_{L_1}, \omega_{L_2} \end{bmatrix}. \tag{49}$$

The original stair PS under study is ontologically implemented with cascade of ideal PGD and NGD two-port circuits as introduced in [22]–[24] for the case of BP-NGD circuit. To illustrate the ideal principle elaborated in the present subsection, we suppose that the reflection coefficients of the ideal PGD and NGD two-port circuits are negligible:

$$|S_{11,22,PGD}(j\omega)| = |S_{11,22,NGD}(j\omega)| = 0.$$
 (50)

The NGD-function based PS explored in [22]–[24] is specified by the phase shift value independent to the frequency on
the band of interest. To obtain such a particular behavior, the
PGD and NGD circuits must fulfil certain specific requirements as introduced in the following paragraphs.

548 2) IDEAL SPECIFICATION OF PGD BLOCK OF THE NGD-PS 549 CIRCUIT

⁵⁵⁰ The ideal specification of the PGD block is defined by ⁵⁵¹ the analytical approach by assuming with the constant



FIGURE 15. Two-port black box of NGD ideal circuit.

(independent of frequency) ideal GD value:

$$GD_{PGD}(\omega) = \tau_a > 0. \tag{51}$$

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Figs. 14 represents the S-matrix block of the perfectly access matched PGD as a two-port circuit which means:

$$S_{11,PGD}(j\omega) = S_{22,PGD}(j\omega) \approx 0.$$
 (52) 556

Therefore, the corresponding S-matrix can be expressed by 557 the ideal equations: 558

$$[S_{PGD}(j\omega)] = \begin{bmatrix} 0 & S_{21,PGD}(j\omega) \\ S_{21,PGD}(j\omega) & 0 \end{bmatrix}$$
(53) 55

knowing that:

$$S_{21,PGD}(j\omega) = S_a \exp\left[j(\varphi_a - \omega\tau_a)\right]$$
(54) 56

with the constant phase, φ_a , and constant magnitude:

$$|S_{21,PGD}(j\omega)| = S_a < 1.$$
 (55) 56

The NGD block must operate in opposite phase of the PGD 564 one. The NGD block ideal specification will be defined in the following paragraph. 566

3) IDEAL SPECIFICATION OF NGD BLOCK OF THE NGD-PS CIRCUIT 568

In this case, let us denote the ideal GD value of NGD block 569 as: 570

$$GD_{NGD}(\omega) = \tau_b < 0. \tag{56}$$

The NGD circuit is assumed with constant magnitude:

$$S_{21,NGD}(j\omega) = S_b < 1$$
 (57) 57

and constant phase:

$$\arg\left[S_{21,NGD}(j\omega)\right] = \varphi_b. \tag{58}$$

Figs. 15 represents the S-matrix blocks of the perfectly access 576 matched NGD system modelled by the ideal equation: 577

$$[S_{NGD}(j\omega)] = \begin{bmatrix} 0 & S_{21,NGD}(j\omega) \\ S_{21,NGD}(j\omega) & 0 \end{bmatrix}$$
(59) 578

where:

$$S_{21,NGD}(j\omega) = S_b \exp\left[j(\varphi_b - \omega\tau_b)\right].$$
 (60) 580



FIGURE 16. Two-port black box of frequency-independent PS constituted by PGD and NGD ideal circuits in cascade.

4) IDEAL REPRESENTATION OF STAIR PS WITH SB-NGDFUNCTION

The associated block is illustrated by the diagram of Fig. 16. Since the reflection coefficients are negligible as defined by equation (50), it should present the S-matrix product as

$$[S_{PS}(j\omega)] = [S_{PGD}(j\omega)] \times [S_{NGD}(j\omega)].$$
(61)

⁵⁸⁷ By means of 2-D matrices introduced in equation (52) and ⁵⁸⁸ equation (59), we have the ideal expression of PS S-matrix ⁵⁸⁹ model:

⁵⁹⁰
$$[S_{PS}(j\omega)] = \begin{bmatrix} 0 & S_{21,PS}(j\omega) \\ S_{21,PS}(j\omega) & 0 \end{bmatrix}$$
 (62)

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⁵⁹²
$$S_{21,PS}(j\omega) = S_a S_b \exp\{j [\varphi_b + \varphi_b - \omega(\tau_a + \tau_b)]\}.$$
 (63)

⁵⁹³ In the frequency band of the study, we can realize a frequency ⁵⁹⁴ independent PS as illustrated by Fig. 17(a) by choosing the ⁵⁹⁵ GD proposed in Fig. 17(b):

$$GD_{NGD}(\omega) = -GD_{PGD}(\omega).$$
(64)

⁵⁹⁷ Therefore, it means that we should have:

$$\tau_b = -\tau_a. \tag{65}$$

⁵⁹⁹ The PGD and NGD associated frequency dependent phase values are given by, respectively:

$$\begin{cases} \varphi_{21,PGD}(\omega) = \arg \left[S_{21,PGD}(j\omega) \right] = \varphi_{21,PGD}(\omega_{L_1}) - \omega \tau_a \\ \varphi_{21,NGD}(\omega) = \arg \left[S_{21,NGD}(j\omega) \right] = \varphi_{21,NGD}(\omega_{L_1}) - \omega \tau_b \end{cases}$$
(66)

5) IDEAL VALUES OF PHASE SHIFT AND GD IN THE EACH604 FREQUENCY BAND OF STAIR STEPS

⁶⁰⁵ The consideration of the dual-band NGD aspect related to ⁶⁰⁶ the SB-NGD function as BW_L and BW_H shown in Fig. 18(a), ⁶⁰⁷ enables to generate a two-step stair PS:

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$$\begin{aligned}
\varphi(\omega_{L_1} \le \omega \le \omega_{L_2}) &= \varphi_1 \\
\varphi(\omega_{L_2} \le \omega \le \omega_{H_1}) &= \varphi_1 - \omega\tau_2 \\
\varphi(\omega_{H_1} \le \omega \le \omega_{H_2}) &= \varphi_2
\end{aligned}$$
(67)

609 with:

$$\begin{cases} \varphi_1 = \varphi(\omega_{L_1}) = -\omega\tau_1 \\ \varphi_2 = \varphi(\omega_{H_1}) = -\omega\tau_3 + \varphi_1 \end{cases}$$
(68)



FIGURE 17. (a) Phase and (b) GD responses of PGD, NGD, and frequency-independent PS.



FIGURE 18. (a) Phase and (b) GD ideal responses of two-step stair PS.

In this case, the GD response can be represented as shown in ⁶¹¹ Fig. 18(b), which is defined as: ⁶¹²

$$\begin{cases} GD(\omega \le \omega_{x1}) = \tau_1 \\ GD(\omega_{x1} \le \omega \le \omega_{x2}) = \tau_2 \\ GD(\omega_{x2} \le \omega \le \omega_{y1}) = \tau_3 \\ GD(\omega_{y1} \le \omega \le \omega_{y2}) = \tau_2 \end{cases}$$
(69) 613

Term Term5 Num=5 Z=R0	+	MLIN TL4 Subst="I W=w	 < MSub1" ្ម	R > R3 > R=R PLC	MLIN TL5 Subst=" W=w]	+ 7	Term Term6 Num=6 Z=R0
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FIGURE 19. Schematic of the designed stair PS prototype.

To validate the feasibility of the introduced ideal principle, a prototype of stair PS circuit PoC will be investigated in the following subsection.

617 B. STAIR PS DESIGN AND MODELLING WITH

618 DISTRIBUTED SB-NGD CIRCUIT

The design of the stair PS is explored in the present subsection. The design is based on the SB-NGD microstrip distributed circuit. The equivalent model between lumped and distributed inductor and capacitor will be proposed.

623 1) DESCRIPTION OF THE DESIGNED PROTOTYPE OF STAIR624 PS POC

To validate the applicative concept, the developed 625 SB-NGD function was used to design a stair PS. The pro-626 totype of stair PS circuit PoC was designed in hybrid tech-627 nology. The PS consists of cascaded PGD constituted by 628 TL and the SB-NGD circuit. The TL was implemented in 629 microstrip technology with physical width, w, and physical 630 total length, d. Fig. 19 represents the schematic of the stair 631 PS PoC designed in the environment of the ADS® elec-632 tronic and RF/microwave simulation tools from Keysight 633 technologies(R). 634

First, a "lumped" PS circuit was designed and simulated with the SB-NGD specified in Table 2. However, the small values of inductor and capacitor are not available in our laboratory. Therefore, a "distributed" PS circuit was designed on Isola Astra 3 dielectric substrate with a surface mounted component (SMC) resistor. The following paragraph will propose the used distributed model of inductor and capacitor.

642 2) MODEL OF MICROSTRIP DISTRIBUTED INDUCTOR AND643 CAPACITOR

⁶⁴⁴ The distributed microstrip structures, inductance and capac-⁶⁴⁵ itance, widths and lengths are denoted by (w_{ind}, d_{ind}) and ⁶⁴⁶ (w_{cap}, d_{cap}) , respectively. During the design phase, we have ⁶⁴⁷ considered the following constants:

- the effective permittivity, ε_{reff} ,
- the center angular frequency, $\omega_0 = 2\pi f_0$,
- $Z_c(w_{ind})$ and $Z_c(w_{cap})$ are the inductor element characteristic impedances,
- and *c* is the vacuum light speed.

⁶⁵³ According to the TL theory, the lumped inductor component ⁶⁵⁴ can be estimated from the distributed physical parameters by the formula:

$$L = \frac{Z_c(w_{ind})\tan(\theta_{ind})}{\omega_0} \tag{70}$$

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with the electrical angle:

$$\theta_{ind} = \frac{\omega_0 d_{ind} \sqrt{\varepsilon_{reff}}}{c}.$$
(71) 658

Under the similar approach, the capacitor component can be estimated from the formula: 655

$$C = \frac{\tan(\theta_{cap})}{\omega_0 Z_c(w_{cap})} \tag{72}$$

with:

$$\theta_{cap} = \frac{\omega_0 d_{cap} \sqrt{\varepsilon_{reff}}}{c}.$$
 (73) 663

By choosing the electrical angle respecting the condition, we can assume that $\tan(\theta_{ind}) \approx \theta_{ind}$ and $\tan(\theta_{cap}) \approx \theta_{cap}$. Consequently, we can estimate the inductor and capacitor formulas introduced in equation (70) and equation (72) as:

$$L \approx \frac{Z_c(w_{ind})d_{ind}\sqrt{\varepsilon_{reff}}}{c}$$
(74) 660

$$C \approx \frac{d_{cap}\sqrt{\varepsilon_{reff}}}{cZ_c(w_{cap})}.$$
 (75) 669

After estimation of the distributed components, the designed 670 stair PS was fabricated. The results are discussed in the 671 following subsection. 672

C. STAIR PS PROTOTYPING AND EXPERIMENTAL VALIDATION RESULTS

The present subsection is focused on the discussion on the successfully fabricated two-step stair PS and also the experimented validation results. Comparisons of results obtained from calculations, simulation with the ADS® electronic and RF/microwave simulation tools from Keysight technologies®, and measurements are discussed.

1) DESCRIPTION OF THE FABRICATED PROTOTYPE OF STAIR 681 PS POC 682

Based on the previously introduced formulas of distributed self-inductor and capacitor, a prototype of hybrid and microstrip circuit was designed, fabricated and tested. The microstrip specifications of substrate susceptible to operate in the expected frequency band of interest are determined. The substrate physical characteristics are addressed in Table 6. The distributed stair PS circuit was implemented.

The layout of the stair PS prototype is shown by Fig. 20(a). 690 The top and bottom view photographs of the fabricated PS 690 prototype are displayed in Fig. 20(b) and Fig. 20(c). This 692 stair PS circuit prototype was tested to extract the measured 693 S-parameter. The following paragraph describes the obtained 7694 results. 695

TABLE 6. Physical parameters of the substrate used in the stair PS circuit.

Structure	Description	Parameters	Values
Cultoteoto	Relative permittivity	\mathcal{E}_r	3
Substrate	Loss tangent	$tan(\delta)$	0.0017
	Thickness	h	0.76 mm
Metallization	Copper conductivity	σ	58 MS/s
conductor	Thickness	t	35 µm
	Length	d	2×9 mm
A agong ling	Width	W	1.53 mm
Access line	Propagation delay	$ au_p$	91.2 ps
SMD component	Resistor	R	62 Ω
Distributed	Length	d_{ind}	5.53 mm
inductance structure	Width	Wind	6.4 mm
Distributed	Length	d_{cap}	12 mm
capacitance structure	Width	W _{cap}	5 mm





³⁹⁶ 2) EXPERIMENTAL SETUP CONFIGURATION

⁶⁹⁷ As experimental validation, the fabricated stair PS proto-⁶⁹⁸ type, previously introduced in Fig. 20, was tested in the ⁶⁹⁹ frequency band from 2 GHz to 3 GHz. Similar to all clas-⁷⁰⁰ sical microwave circuits, the stair PS SB-NGD test is based ⁷⁰¹ on the S-parameter analysis. The tests were realized with



FIGURE 21. Configuration of the stair PS SB-NGD prototype experimental setup.

 TABLE 7. Specifications of the tested two-step stair PS.

Demonstern	Lumped		Distributed		Measurement	
Parameters	BW_L	BW_H	BW_L	BW_H	BW_L	BW_H
$f_{\min}(\text{GHz})$	2	2.6	2	2.6	2	2.6
$f_{\rm max}({\rm GHz})$	2.3	3.0	2.3	2.9	2.3	2.9
$\varPhi_{mean}\left(^{\circ} ight)$	-66	-102	-67.4	-103	-70	-104
⊿Ф (°)	+/-2.1	+/-3.2	+/-3	+/-2.4	+/-4	+/-2
$\Delta S_{21}(f_o)$ (dB)	0.82	1.35	1	1.28	0.88	0.94

10 MHz to 26.5 GHz PNA-X N5242A Network Analyzer702from Keysight Technologies®. The experimental setup can703be seen in Fig. 21.704

During the measurement campaign, the test was made ⁷⁰⁵ under SOLT calibration. The next paragraph will discuss ⁷⁰⁶ between the simulated and measured results. ⁷⁰⁷

3) STAIR PS PROTOTYPE MEASUREMENT VALIDATION

Fig. 22 displays the comparisons between the (lumped and
distributed) simulated and measured phase shift and GD
results. As expected, they confirm undeniably the two-step
stair PS functions. This PoC confirms the feasibility of stair
PS. Table 7 summarizes the stair PS specifications.710711
712712

A good correlation of stair phase values can be underlined 714 with the measured one: 715

- In the first bandwidth, $BW_L = 2-2.3$ GHz, where we 716 have a phase shift of $-70^{\circ} \pm 4^{\circ}$. 717
- In the 2nd bandwidth, $BW_H = 2.6-3.0$ GHz, the step 718 phase is shifted to $-104^{\circ}\pm 2^{\circ}$. 719



FIGURE 22. Simulated and measured, (a) transmission phase and (b) GD of the stair PS shown in Fig. 20.



FIGURE 23. Simulated and measured (a) S₁₁ and (b) S₂₁ of the stair PS shown in Fig. 20.

Furthermore, the associated reflection and transmission 720 coefficients of the stair PS PoC are plotted in Fig. 23. They 721 show a good access matching between the two bands (BW_L) 722 and BW_H) and the PS flatness transmission coefficient less 723 than 3 dB through the whole range (2-3 GHz). 724

VII. CONCLUSION

An original theory of SB-NGD circuit is presented. The 726 proposed SB-NGD passive topology was inspired from 727 the LP-NGD cell and the LP-to-SB circuit transform. The 728 S-parameter model is established for the NGD analysis. The 729 different properties of the SB-NGD function are developed. 730

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To confirm the feasibility of the SB-NGD theory, a circuit 731 PoC has been designed and simulated. Sensitivity analyses 732 with respect to the constituting lumped component parame-733 ters are performed. It was reported how the SB-NGD response 734 can be sensitivity to the three circuit parameters. An example 735 of SB-NGD circuit application is developed to design a stair 736 PS function with phase shift independent to the frequency. 737 The principle of the stair PS is introduced. Simulations and 738 experimentations illustrate the feasibility of the SB-NGD 739 circuit-based stair PS in two frequency bandwidths. 740

The present research result is a pioneering work about the 741 design of the future communication system. In this optic, 742 the developed stair PS concept can be useful in the future 743 for designing phase array system of innovative multi-beam 744 antenna for the improvement of RF and microwave system 745 control [41]. 746

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