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Compact Broadband Negative Group Delay Circuit with Flatness and Bandwidth Enhancement

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Abstract: A novel compact broadband negative group delay (NGD) circuit with flatness and bandwidth enhancement is presented. The presented negative group delay circuit (NGDC) consists of a high-impedance transmission line connected by two resistors, which are linked together with two coupled lines and a low-impedance transmission line. The flatness of the NGD is enhanced by tuning the characteristic impedance of the transmission lines. In order to verify the method, a compact broadband NGDC with a size of $29.4 \text{ mm} \times 58.1 \text{ mm}$ ($0.14 \lambda_g \times 0.29 \lambda_g$) is designed, fabricated, and measured at the center frequency of 1.0 GHz. The measured results show that an NGD time of -0.49 ns at the center frequency is obtained with return loss and insertion loss of 35.0 dB and 18 dB, respectively. And, the flat-NGD bandwidth reaches 509 MHz (50.9%) over 0.766 to 1.275 GHz with 19% group-delay fluctuation.

Keywords: bandwidth enhancement; group delay flatness; negative group delay; compact broadband



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1. Introduction

Recently, negative group delay circuits (NGDCs) have attracted more attention due to their potential applications. The NGDCs have been employed for amplifiers to achieve group delay (GD) equalization [1], to achieve the compensation of the beam squint in series-fed antenna arrays [2] and to improve the performance of signal anticipation [3], and kinds of filters were designed with the NGD characteristic [4–6]. In [7], the NGDCs were used in designing non-foster components. Furthermore, reconfigurable non-foster circuits with NGDCs were designed [8]. Besides, the compensation of GD [9] or the anticipation of the mechanical actuators' signals [10] can be achieved by cascading the NGDCs and other components. In order to obtain high performance, some NGDCs based on new methods such as filter theory [11], signal interference techniques [12], lossy transmission lines [13] and split-ring resonators [14] have been presented. However, the GD near the center frequency is not flat and cannot satisfy wideband applications such as the broadband phase shifter [15].

In order to increase the flatness of the GD, several flat-NGDCs have been presented [16–24]. In accordance with filter theory, a 4.3% flat-NGD bandwidth of a NGDC with a ripple of 16% was achieved [16]. In [17], through bringing the two working frequencies of the dual-band NGDC closer, a flat-NGDC was designed. But the absolute flattening of GD cannot be achieved in theory. Afterwards, power dividers with flat-NGD characteristics were proposed in [18–20]. In addition, based on the transmission lines with step impedance or T-type structures, a flat NGD characteristic with an NGD time of -0.5 ns and -1.11 ns was achieved [21,22]. Nevertheless, the circuit size was not small enough. To achieve the size reduction, two NGDCs based on two TL structures and three coupled lines were presented, respectively [23,24]. However, the ideal port matching characteristics could not be obtained, and the circuit size needed to be further enhanced.

In this paper, a compact broadband NGDC is presented to achieve flat-NGD characteristics and ideal port matching. The presented NGDC consists of two couple lines connected

by a transmission line and two resistors linked with a transmission line. The couple lines are utilized to improve the port matching characteristics and the two transmission lines are used to strengthen the flatness of the NGD response. And, the equivalent of the open-circuited coupled line is a Π structure [25]. Therefore, compared with the circuit in [23], the proposed circuit structure with the coupled lines is completely different. Furthermore, under the condition of the flat-NGD characteristic, the ideal port matching of the proposed circuit is realized. The circuit and design process are presented and discussed.

2. Circuit Structure and Design Theory

2.1. Even- and Odd-Mode Analysis

Figure 1 gives the configuration of the proposed compact broadband NGDC. It consists of two couple lines with even- and odd-mode characteristic impedance Z_{0e} , Z_{0o} and electrical length θ , which is connected by a transmission line with characteristic impedance Z_1 and electrical length θ_1 , and two resistors R link, by transmission line, with characteristic impedance Z_2 and electrical length θ_2 .

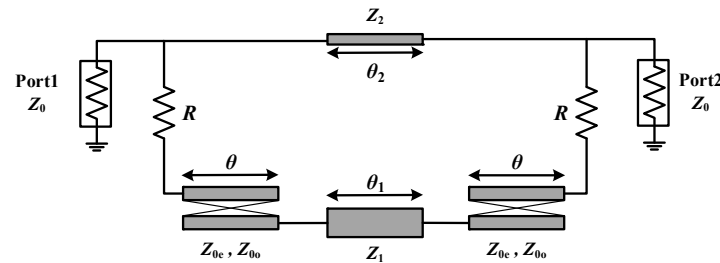


Figure 1. Configuration of the proposed NGD microwave circuit.

The even- and odd-mode equivalent circuits of the proposed NGDC is shown in Figure 2. And, the even- and odd-mode input impedance Z_{in_odd} and Z_{in_even} can be expressed as

$$Z_{in_odd} = A_1 + jA_2, \quad (1)$$

$$Z_{in_even} = A_3 + jA_4, \quad (2)$$

where A_1 , A_2 , A_3 and A_4 are given in Equations (3)–(6).

$$A_1 = \frac{Z_2^2 R}{[Z_2 + M_{odd} \cot(\theta_2/2)]^2 + R^2 \cot^2(\theta_2/2)}, \quad (3)$$

$$A_2 = \frac{Z_2^2 M_{odd} + Z_2 M_{odd}^2 \cot(\theta_2/2) + Z_2 R^2 \cot(\theta_2/2)}{[Z_2 + M_{odd} \cot(\theta_2/2)]^2 + R^2 \cot^2(\theta_2/2)}, \quad (4)$$

$$A_3 = \frac{Z_2^2 R}{[Z_2 - M_{even} \tan(\theta_2/2)]^2 + R^2 \tan^2(\theta_2/2)}, \quad (5)$$

$$A_4 = \frac{Z_2^2 M_{even} - Z_2 M_{even}^2 \tan(\theta_2/2) - Z_2 R^2 \tan(\theta_2/2)}{[Z_2 - M_{even} \tan(\theta_2/2)]^2 + R^2 \tan^2(\theta_2/2)}, \quad (6)$$

where the expression of M_{odd} and M_{even} are

$$M_{odd} = \frac{Z_{0e} - Z_{0o}}{2} \times \frac{2Z_1 \tan(\theta_1/2) - 2Z_{0o} \cot \theta + (Z_{0e} - Z_{0o}) \tan \theta}{Z_{0e} + Z_{0o} - 2Z_1 \tan(\theta_1/2) \tan \theta} - Z_{0o} \cot \theta, \quad (7)$$

$$M_{even} = \frac{Z_{0e} - Z_{0o}}{2} \times \frac{-2Z_1 \cot(\theta_1/2) - 2Z_{0o} \cot \theta + (Z_{0e} - Z_{0o}) \tan \theta}{Z_{0e} + Z_{0o} + 2Z_1 \cot(\theta_1/2) \tan \theta} - Z_{0o} \cot \theta, \quad (8)$$

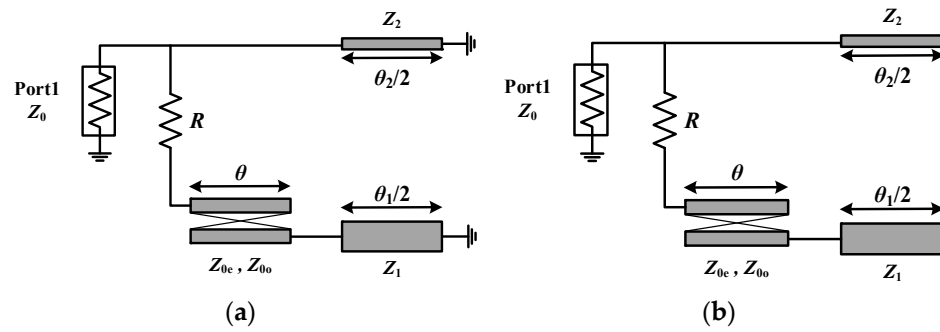


Figure 2. Odd- and even-mode equivalent circuits. (a) Odd-mode; (b) even-mode.

And then the S -parameters of the presented compact broadband NGDC are expressed as

$$S_{11} = \frac{Z_{\text{in_odd}}Z_{\text{in_even}} - Z_0^2}{(Z_{\text{in_odd}} + Z_0)(Z_{\text{in_even}} + Z_0)}, \quad (9)$$

$$S_{21} = \frac{(Z_{\text{in_even}} - Z_{\text{in_odd}})Z_0}{(Z_{\text{in_odd}} + Z_0)(Z_{\text{in_even}} + Z_0)} = \frac{X_1 + jX_2}{X_3 + jX_4}, \quad (10)$$

where Z_0 is the port impedance. The unknown parameters in Equation (10) are

$$X_1 = (A_3 - A_1)Z_0, \quad (11)$$

$$X_2 = (A_4 - A_2)Z_0, \quad (12)$$

$$X_3 = (A_1 + Z_0)(A_3 + Z_0) - A_2A_4, \quad (13)$$

$$X_4 = A_2(A_3 + Z_0) + A_4(A_1 + Z_0), \quad (14)$$

Furthermore, the GD of the presented NGDC can be expressed as

$$\tau_g = -\frac{d\angle S_{21}}{d\omega}, \quad (15)$$

2.2. S -Parameters and NGD Analysis

In the proposed compact broadband NGDC, the electronic length is assumed as $\theta_1 = \theta_2 = \theta = \pi/2$ at center frequency f_0 . When the electronic lengths in Equations (1)–(15) are $\pi/2$, the simplification of S -parameters and GD at f_0 are

$$S_{11}(f_0) = \frac{A_{10}^2 + A_{20}^2 - Z_0^2}{(A_{10} + jA_{20} + Z_0)(A_{10} - jA_{20} + Z_0)}, \quad (16)$$

$$S_{21}(f_0) = \frac{2A_{20}Z_0}{A_{10}^2 + A_{20}^2 + Z_0^2 + 2A_{10}Z_0}, \quad (17)$$

$$GD(f_0) = \frac{A'_{10}}{A_{20}} + \frac{2A_{10}A'_{20} + 2Z_0A'_{20} - 2A'_{10}A_{20}}{A_{10}^2 + A_{20}^2 + Z_0^2 + 2A_{10}Z_0}, \quad (18)$$

where the unknown parameters are given as

$$A_{10} = \frac{Z_2^2 R}{(Z_2 - P)^2 + R^2}, \quad (19)$$

$$A_{20} = \frac{-Z_2^2 P + Z_2 P^2 + Z_2 R^2}{(Z_2 - P)^2 + R^2}, \quad (20)$$

$$A'_{10} = -\frac{[2(Z_2 - P)(Q + P\tau_2) - 2R^2\tau_2]Z_2^2R}{[(Z_2 - P)^2 + R^2]^2}, \quad (21)$$

$$A'_{20} = \frac{(Z_2^2Q - 2Z_2PQ - Z_2P^2\tau_2 - Z_2R^2\tau_2)[(Z_2 - P)^2 + R^2] - [2(Z_2 - P)(Q + P\tau_2) - 2R^2\tau_2](-Z_2^2P + Z_2P^2 + Z_2R^2)}{[(Z_2 - P)^2 + R^2]^2}, \quad (22)$$

$$\tau_i = \theta_i / 2\pi f_0 (i = 1, 2), \quad (23)$$

where P and Q can be expressed as

$$P = \frac{(Z_{0e} - Z_{0o})^2}{4Z_1}, \quad (24)$$

$$Q = \frac{(Z_{0e} - Z_{0o})\tau}{2} + \frac{(Z_{0e} - Z_{0o})^2(Z_{0e} + Z_{0o})\tau}{8Z_1^2} + \frac{(Z_{0e} - Z_{0o})^2\tau_1}{4Z_1} + Z_{0o}\tau, \quad (25)$$

$$\tau = \theta / 2\pi f_0, \quad (26)$$

As can be seen from the expressions of $S_{11}(f_0)$, $S_{21}(f_0)$ and $GD(f_0)$ in Equations (16)–(18), there are four variables Z_2 , R , P and Q in them. So, if Z_2 is determined, the values of R , P and Q can be solved for. Once P and Q are known, there are only three variables, Z_1 , Z_{0e} and Z_{0o} , in Equations (24) and (25). When Z_1 is determined, the values of Z_{0e} and Z_{0o} can also be solved for.

Therefore, it is a must to determine the desired values of the $S_{11}(f_0)$, $S_{21}(f_0)$ and $GD(f_0)$ ahead and chose proper values of the free variables Z_1 and Z_2 during the design.

2.3. Free Variables Analysis

Based on the theory in Section 2.2, when $S_{11}(f_0) = 0$ for port matching, the values of $S_{21}(f_0)$ and $GD(f_0)$ can be selected according to different needs of designers. In this section, the GD and S -parameters, especially the flat-NGD bandwidth and flatness, of the free variables Z_1 and Z_2 at different values will be discussed.

Figure 3 gives the influences of Z_2 on the GD and S -parameters. It can be seen that when Z_2 increases from 140 Ω to 160 Ω , the ripple of $\tau_g \times f_0$ near the center frequency f_0 increases. Moreover, $|S_{11}|$ and $|S_{21}|$ change a little within the flat-NGD bandwidth. Consequently, Z_2 can be employed to additionally improve the flatness of GD .

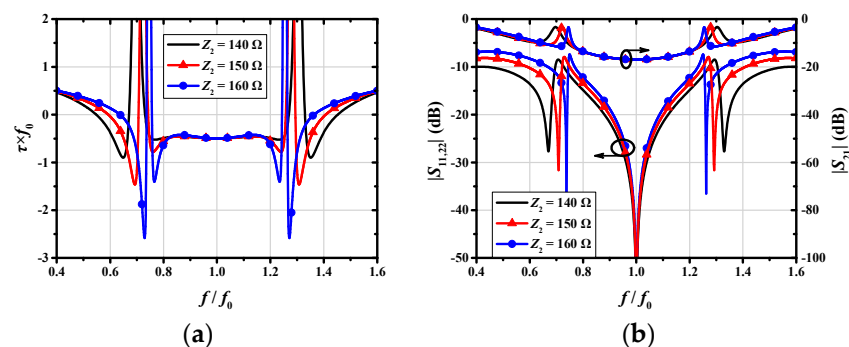


Figure 3. The performance at different Z_2 values with fixed $Z_1 = 60 \Omega$, $\tau_g \times f_0 = -0.5$ and $|S_{21}| = -17$ dB at f_0 . (a) $\tau_g \times f_0$; (b) S -parameters.

The changes in circuit performances with different values for Z_1 are given in Figure 4. As can be seen, when Z_2 increases from 55 Ω to 65 Ω , the ripple of $\tau_g \times f_0$ near the center frequency f_0 decreases. Moreover, $|S_{11}|$ and $|S_{21}|$ remain unchanged within the flat-NGD bandwidth. Consequently, Z_1 can also be used to achieve the GD flatness enhancement.

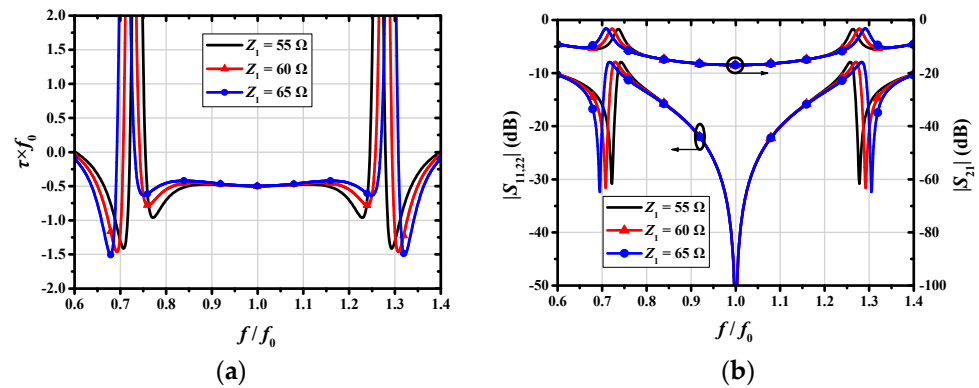


Figure 4. The performance at different Z_1 values with fixed $Z_2 = 150 \Omega$, $\tau_g \times f_0 = -0.5$ and $|S_{21}| = -17$ dB at f_0 . (a) $\tau_g \times f_0$; (b) S -parameters.

Figure 5 shows the effect of different Z_1 and Z_2 couples on the entire circuit's performance. It can be seen that the flat-NGD characteristic can be achieved by adjusting the value of Z_1 and Z_2 . Meanwhile, it is also demonstrated that the design method can achieve different NGD values compared to Figures 3 and 4. Besides, it also can be obtained from Figures 3–5; once the $|S_{21}|$ and $\tau_g \times f_0$ at f_0 are fixed, the maximum flat-NGD bandwidth is unchanged.

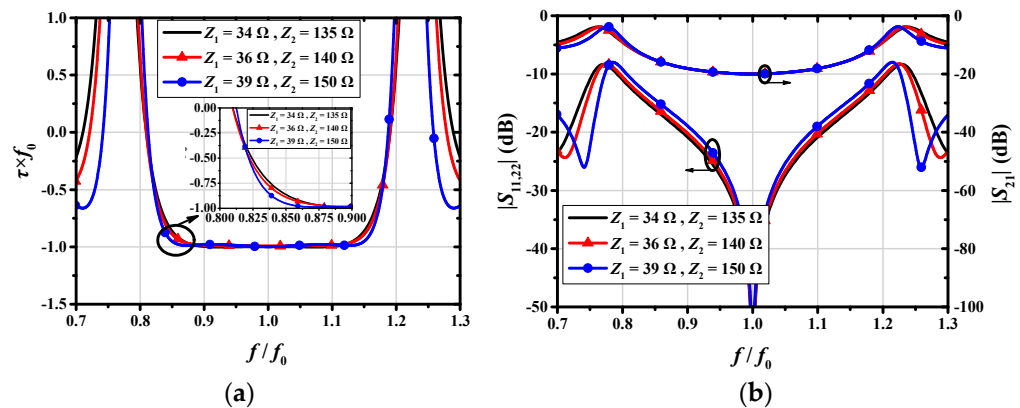


Figure 5. The performance at different Z_1 and Z_2 values with fixed $\tau_g \times f_0 = -1.0$ and $|S_{21}| = -20$ dB at f_0 . (a) $\tau_g \times f_0$; (b) S -parameters.

It is worthy to note the effect of different values for $|S_{21}|$ on the entire circuit performance when the Z_1 , Z_2 and NGD values are fixed at f_0 . As can be seen in Figure 6, when $|S_{21}|$ decreases from -16 dB to -18.5 dB, the ripple of $\tau_g \times f_0$ near the center frequency f_0 also decreases. Therefore, the NGD time, $|S_{21}|$ and flat-NGD bandwidth need to be considered comprehensively.

For the discussion of the maximum flat-NGD bandwidth, Figure 7 gives the $\tau_g \times f_0$ and S -parameters under the same $|S_{21}|$ with that in Figure 6. To obtain the maximum flat-NGD bandwidth, the values of Z_1 and Z_2 are changed in Figure 7. It can be seen that the maximum flat-NGD bandwidth increases with the $|S_{21}|$ decreases.

For convenience, a simple design process of the proposed circuit is summarized as follows.

- Step 1: Determine the desired $|S_{21}|$ and NGD time at the center frequency f_0 .
- Step 2: Choose a proper Z_2 according to Figures 3 and 5. Then, calculate R , P and Q using Equations (16)–(23).
- Step 3: Select an appropriate Z_1 according to Figures 4 and 5. Then, calculate Z_{0e} and Z_{0o} using Equations (24)–(26).
- Step 4: If the flatness of GD is not enough after the first three steps, return to Step 2 and adjust Z_1 and Z_2 to other potential values.

Step 5: If the flatness of GD is not enough or the maximum flat-NGD bandwidth is not satisfied after the first four steps, return to Step 1 and adjust $|S_{21}|$.

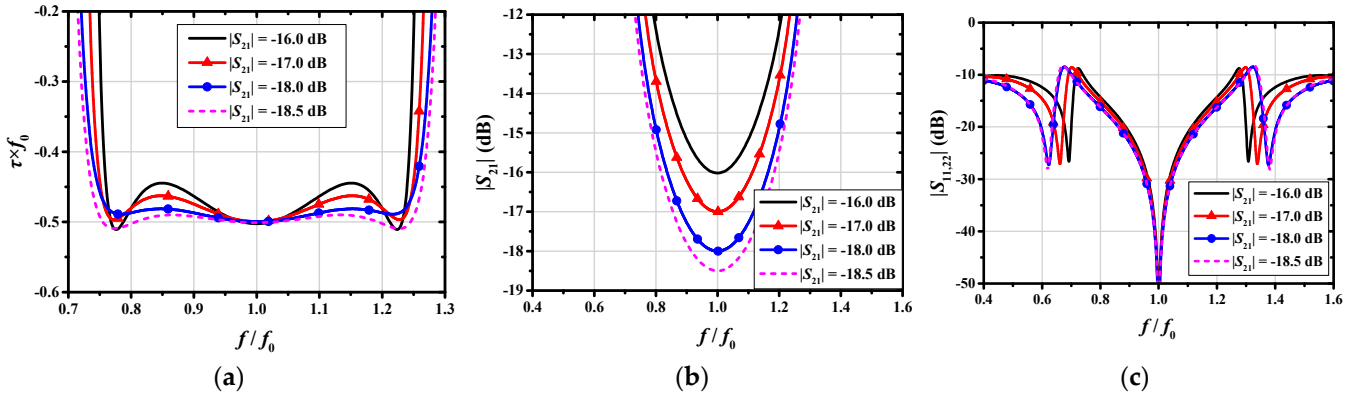


Figure 6. The performance with different $|S_{21}|$ values with fixed $Z_1 = 60 \Omega$, $Z_2 = 150 \Omega$ and $\tau_g \times f_0 = -0.5$ at f_0 . (a) $\tau_g \times f_0$; (b) $|S_{21}|$; (c) $|S_{11,22}|$.

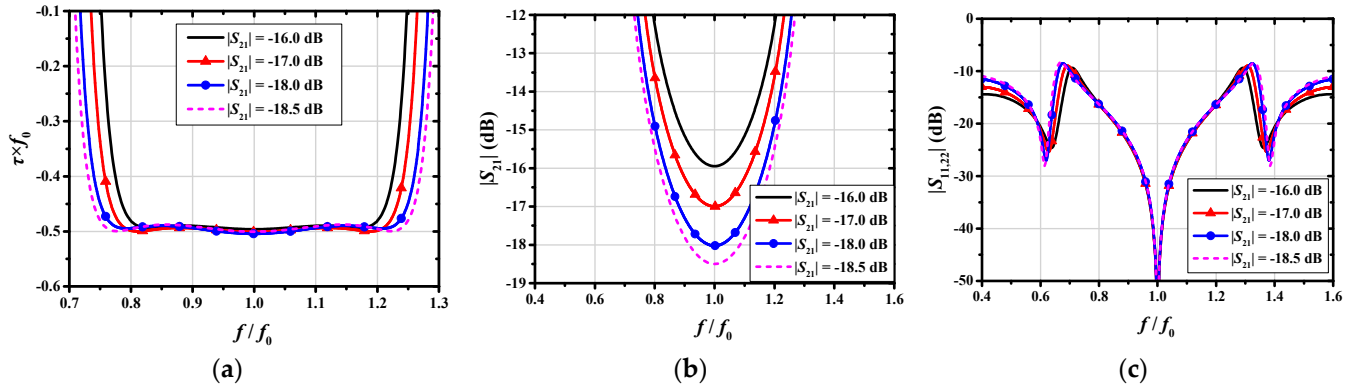


Figure 7. The performance with different $|S_{21}|$ values with fixed $\tau_g \times f_0 = -0.5$ at f_0 . (a) $\tau_g \times f_0$; (b) $|S_{21}|$; (c) $|S_{11,22}|$.

3. Experimental Verification

To confirm the design concept, a compact broadband NGDC is designed at the center frequency $f_0 = 1.0$ GHz with $\text{GD} = -0.5$ ns. Using the design procedures in Section 2, the electrical parameters can be obtained as $Z_1 = 59 \Omega$, $Z_2 = 150 \Omega$, $Z_{0e} = 74.6 \Omega$, $Z_{0o} = 39.1 \Omega$, $R = 52 \Omega$. Then the flat-NGDC is implemented on the substrate with a thickness of 1.0 mm, with a dielectric constant of 2.65 and a loss tangent of 0.003. The layout of the proposed compact broadband NGDC is given in Figure 8a. After optimizing by HFSS EM 2018 software, the final physical dimensions are $w_1 = 2.0$ mm, $l_{11} = 7.0$ mm, $l_{12} = 23.0$ mm, $l_{13} = 5.0$ mm, $w_2 = 0.2$ mm, $l_{21} = 6.5$ mm, $l_{22} = 17.8$ mm, $l_{23} = 6.9$ mm, $w = 2.0$ mm, $s = 0.2$ mm, $l = 49.0$ mm, $w_p = 1.8$ mm, $l_p = 5.0$ mm, with $R = 50 \Omega$. The photo of the fabricated compact broadband NGDC is given in Figure 8b. The overall circuit dimension is $29.4 \text{ mm} \times 58.1 \text{ mm}$ ($0.14 \lambda_g \times 0.29 \lambda_g$, where λ_g is the guided wavelength of 50- Ω TLs at the center frequency). The measurements are completed by an AV3565A network analyzer manufactured in China Electronics Technology Group Corporation 41st Research Institute, Beijing, China.

Figure 9 shows the measured GD and S-parameters, along with the simulated and calculated results for comparison. It can be seen from Figure 9a that the calculated, simulated and measured flatness and GD (f_0) are basically consistent. And, the measured flat-NGD bandwidth is slightly offset directly from the simulated one. A relatively good consistency for calculated, simulated and measured $|S_{21}|$ has been shown in Figure 9b. The calculated $|S_{11}|$ and $|S_{22}|$ at f_0 is minimized, which means the port is matching ideally. And, the simulated and measured $|S_{11}|$, $|S_{22}|$ has a slight frequency shift, but good port

matching characteristics are implemented within the flat-NGD bandwidth. The differences between the measured results and the simulated results are due to the inaccuracy of the substrate parameters.

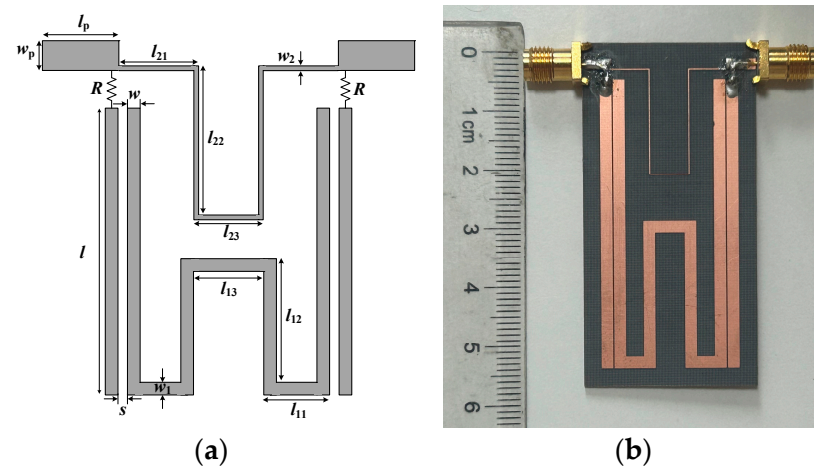


Figure 8. The proposed compact broadband NGDC. (a) Layout; (b) Photograph.

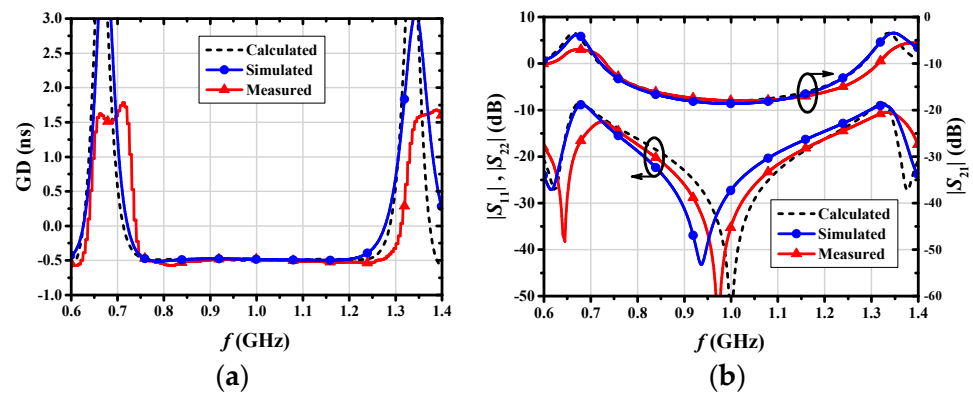


Figure 9. Calculated, simulated and measured results of the proposed compact broadband NGDC. (a) GD; (b) S -parameters.

The measured GD, $|S_{21}|$ and $|S_{11}|$ at f_0 are -0.48 ns, -18 dB and -35 dB, respectively. The measured NGD bandwidth of the presented NGDC is 569 MHz (56.9%) over 741 to 1310 MHz; meanwhile, the flat-NGD bandwidth is 509 MHz (50.9%) over 766 to 1275 MHz. And, the input/output return loss is better than 13 dB within the flat-NGD bandwidth. The insertion loss bandwidth, which is defined as the 3-dB variation from the center frequency $|S_{21}|$, is 439 MHz (43.9%) over 800 to 1239 MHz. The comparisons of the presented NGDC with precious works are given in Table 1. Compared with [21,23,24], they have a close center frequency and NGD time, but the presented NGDC has the largest flat-NGD bandwidth with a moderate IL. For a better comparison, the figure of merits (FOM_1 and FOM_2) have been used, which are defined as [22]

$$FOM_1 = |\tau_g(f_0)| \times BW_{\text{flat-NGD}} \times |S_{21}(f_0)|, \quad (27)$$

$$FOM_2 = |\tau_g(f_0)| \times BW_{\text{flat-NGD}} \times |S_{21}(f_0)| / FOM_1, \quad (28)$$

Table 1. Performance comparison between the proposed compact broadband NGDC and previous flat-NGD circuits.

Refs.	f_0 (GHz)	NGD (ns)	GD Ripple (%)	Flat-NGD Bandwidth (%)	IL (dB)	Size ($\lambda_g \times \lambda_g$)	FOM ₁ /FOM ₂ ($\times 10^{-3}$)
[18]	2.14	−0.49	16	14.7	16.6	0.73×1.01	23.2/21.5
[19]	2.14	−0.20	40	9.30	14.0	0.68×0.41	8.0/28.7
[20]	2.00	−0.88	25	9.50	33.1	0.41×0.51	3.7/17.7
[21]	1.00	−0.50	16	46.3	18.8	0.24×0.34	26.4/325.9
[22]	2.14	−1.11	23	6.10	9.75	0.65×1.18	46.9/61.1
[23]	0.68	−0.49	10	31.8	15.3	0.20×0.38	26.8/352.2
[24]	0.94	−0.54	14	35.0	18.3	0.09×0.48	21.6/501.4
This Work	1.00	−0.48	19	50.9	18.0	0.14×0.29	30.8/757.6

It can be seen from Table 1 that the proposed NGDC has a larger FOM₁ and FOM₂ than [18–24] with a moderate GD ripple. Moreover, the circuit size of the proposed NGDC is the smallest.

4. Conclusions

In this paper, a compact broadband NGDC has been proposed, and the design equations at the center frequency have been simplified. The free variables (Z_1 and Z_2) used to achieve the enhancement of the GD flatness have been discussed. An NGDC with a size of $0.14 \lambda_g \times 0.29 \lambda_g$ has been designed, simulated, fabricated and measured. A very good agreement is confirmed by simulation and measurement results. Compared to the existing flat-NGDCs, the presented NGDC has a larger FOM₁ and FOM₂ with moderate GD ripple and the smallest circuit size.

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Conflicts of Interest: The authors declare no conflicts of interest.

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