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Arbitrary terminated negative group delay circuit using signal interference concept

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Abstract

In this article, we demonstrate signal interference concept based wideband negative group delay (NGD) circuit with an arbitrary termination port impedance. The proposed circuit consists of unequal power division ratio 180° hybrid and in-phase combiner. The NGD can be generated by controlling power division ratios of 180° hybrid and combiner. For experimental verification, the circuit is designed and fabricated at a center frequency of 2 GHz. The experiment results show that the proposed NGD circuit can provide 460 MHz NGD bandwidth (bandwidth of group delay <0 ns) with group delay of −0.8 ns at 2 GHz.

KEYWORDS

arbitrary termination impedance, hybrid, signal interference concept, wideband negative group delay

1 | INTRODUCTION

Propagation of electromagnetic waves in dispersive media can be characterized by phenomena including abnormal phase, group delays, and velocities.[1] In a specific frequency band of an anomalous dispersion, the abnormal group delay velocity is observed to be greater than speed of light in vacuum or even negative value. This phenomenon is defined as superluminal group velocity or negative group delay (NGD).[2] Theoretical and experimental investigations in fields of electronic and microwave engineering have confirmed that different active and passive circuit topologies can generate the NGD phenomenon under signal attenuation conditions.

Researchers have been trying to find applications of NGD or the superluminal effect to various electronics circuits. Therefore, the NGD circuits are widely used in various applications in microwave circuits and systems that include shortening or reducing delay lines, enhancing the efficiency of feedforward amplifier, enhancing the bandwidth of feedback linear amplifier, minimizing beam-squint in phased array antenna, and realization of non-Foster reactive elements.[3-6]

Since NGD occurs when signal attenuation is maximum; conventional approaches to realize NGD circuits are based on RLC resonators, which have smaller NGD bandwidth and magnitude (S_{21}) flatness.[7-13] To mitigate these problems, researchers have attempted to design

NGD circuits using different methods such as cross-coupling between resonators,[14] increasing the number of resonators,[15] and transversal-filter topologies.[16] Except for the work in Reference 16, these NGD circuits also used resistor R for generating NGD, which prevented fully distributed circuit realization.

Recently, signal interference technique has been adopted to realize NGD circuit.[17,18] In Reference 17, unequal power divider/combiner and coupled-line phase shifter are utilized to generate NGD, however, circuit can only grant narrow NGD bandwidth (group delay <0) as well as group delay (GD) and magnitude flatness bandwidth. Similarly, two transmission lines along with resistors arranged in parallel creating two paths have been used to generate NGD in Reference [18], which has poor return losses. In addition, none of these works have arbitrary termination port impedances.

In this article, we demonstrate an arbitrary termination port impedance wideband NGD circuit based on signal interference concept. The proposed circuit utilizes power division ratios of 180° hybrid and combiner to generate wideband NGD.

2 | DESIGN THEORY AND PHYSICAL CIRCUIT IMPLEMENTATION

2.1 | Analytical design theory

Figure 1 shows the proposed structure of an arbitrary terminated wideband NGD circuit. The proposed circuit consists of 180° hybrid and in-phase combiner. For 180° hybrid shown in Figure 1, it is well known that excited power at port 1 is split between port a and b.[19] Similarly, in-phase combiner combines signal powers coming through port a and b. Assuming power division ratios of hybrid and in-phase combiner as k_h^2 and k_c^2, respectively, the transmission coefficients of hybrid and combiner through path I and II are defined as shown in (1).[19]

$$S_{a1h} = \frac{k_h}{\sqrt{1+k_h^2}} e^{-j\varphi_{a1h}} \tag{1a}$$

$$S_{b1h} = \frac{1}{\sqrt{1+k_h^2}} e^{-j\varphi_{b1h}} \tag{1b}$$

$$S_{b2c} = \frac{1}{\sqrt{1+k_c^2}} e^{-j\varphi_{b2c}} \tag{1c}$$

$$S_{a2c} = \frac{k_c}{\sqrt{1+k_c^2}} e^{-j\varphi_{a2c}}, \tag{1d}$$

where subscript h and c represent hybrid and in-phase combiner, respectively. The overall transmission coefficient of the proposed NGD circuit can be derived as in (2) by using circuit theory as shown in Figure 1.

$$S_{21} = \frac{k_h k_c}{\sqrt{1+k_c^2}\sqrt{1+k_h^2}} e^{-j(\varphi_{a1h}+\varphi_{a2c})} + \frac{k_c}{\sqrt{1+k_h^2}\sqrt{1+k_c^2}} e^{-j(\varphi_{b1h}+\varphi_{a2c})} \tag{2}$$

Using phase of S_{21}, the GD of the proposed NGD circuit can be written as (3)

$$\tau_{21} = \tau_{b1h} + \tau_{b2c} - \frac{k_c}{k_h - k_c}(\tau_{a1h} - \tau_{b1h} + \tau_{b2c} - \tau_{a2c}) \tag{3}$$

From (3), the proposed circuit can only provide the NGD if $\tau_{b2c} \simeq \tau_{a2c}$ and the conditions in (4) are satisfied.

$$\tau_{b1h} > \tau_{a1h} \tag{4a}$$

$$k_h < k_c \tag{4b}$$

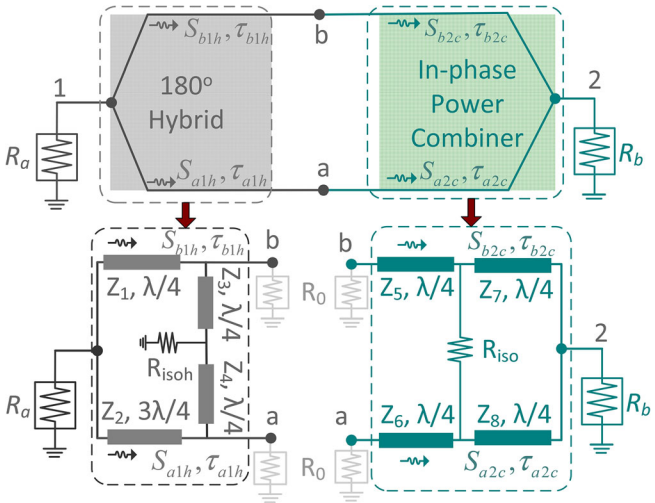

FIGURE 1 Proposed structure of wideband negative group delay circuit based on signal interference concept

2.2 | Circuit Implementation

To implement the proposed topology, the 180° hybrid and in-phase combiner are implemented with arbitrary

terminated ring hybrid and Wilkinson power divider, respectively, as shown in Figure 1. To match all ports, the characteristic impedances of transmission lines can be derived as shown in (5).[19]

$$Z_1 = \sqrt{\left(1+k_h^2\right)R_aR_0} \tag{5a}$$

$$Z_2 = \sqrt{\frac{R_aR_0\left(1+k_h^2\right)}{k_h^2}} \tag{5b}$$

$$Z_3 = \sqrt{\frac{R_{isoh}R_0\left(1+k_h^2\right)}{k_h^2}} \tag{5c}$$

$$Z_4 = \sqrt{R_{isoh}R_0\left(1+k_h^2\right)} \tag{5d}$$

$$Z_5 = \sqrt{Z_{ad}R_0} \tag{5e}$$

$$Z_6 = \sqrt{k_c^2Z_{ad}R_0} \tag{5f}$$

$$R_{isoc} = Z_{ad}\left(1+k_c^2\right) \tag{5g}$$

$$Z_7 = \sqrt{\frac{Z_{ad}R_b\left(1+k_c^2\right)}{k_c^2}} \tag{5h}$$

$$Z_8 = \sqrt{Z_{ad}R_bk_c^2\left(1+k_c^2\right)}, \tag{5i}$$

where R_a and R_b are arbitrarily terminated port impedances. Similarly, R_{isoh} and R_0 are arbitrary resistances. Additionally, Z_{ad} is an arbitrary real positive resistance. Magnitude of S_{21} and GD at a center frequency (f_0) can be simplified as shown in (6) using (2) and (3).

$$|S_{21}|_{f=f_0} = \frac{|k_c-k_h|}{\sqrt{\left(1+k_h^2\right)\left(1+k_c^2\right)}} \tag{6a}$$

$$\tau_{21}|_{f=f_0} = \tau_{b1h}|_{f=f_0} + \tau_{b2c}|_{f=f_0} - \frac{k_c\left(\tau_{a1h}-\tau_{b1h}+\tau_{b2c}-\tau_{a2c}\right)|_{f=f_0}}{k_h-k_c}, \tag{6b}$$

where

$$\tau_{b1h}|_{f=f_0} = \frac{R_a\left(1+3k_h+k_h^2+3k_h^3\right)-\left(1-6k_h-3k_h^3\right)R_0}{8f_0\left(1+k_h^2\right)\sqrt{\left(1+k_h^2\right)R_aR_0}} \tag{7a}$$

$$\tau_{a1h}|_{f=f_0} = \frac{\left(1+k_h+k_h^2+k_h^3\right)R_a+\left(1+2k_h^2-k_h^3\right)R_0}{4f_0\left(1+k_h^2\right)\sqrt{\left(1+k_h^2\right)R_aR_0}} \tag{7b}$$

$$\tau_{b2c}|_{f=f_0} = \frac{1}{8f_0}\left(\frac{Z_{ad}+R_0}{\sqrt{Z_{ad}R_0}} + \frac{R_b\left(1+k_c^2\right)+k_c^2Z_{ad}}{\sqrt{\left(1+k_c^2\right)k_c^2R_bZ_{ad}}}\right) \tag{7c}$$

$$\tau_{a2c}|_{f=f_0} = \frac{1}{8f_0}\left(\frac{Z_{ad}k_c^2+R_0}{\sqrt{Z_{ad}k_c^2R_0}} + \frac{R_b\left(1+k_c^2\right)+k_c^2Z_{ad}}{\sqrt{\left(1+k_c^2\right)k_c^2R_bZ_{ad}}}\right) \tag{7d}$$

For validation of analytical design equations, the simulated response for the proposed circuit is shown in Figure 2 using ideal circuit parameters. As observed from these results, the NGD fractional bandwidth (FBW) defined as NGD bandwidth (GD < 0)/f_0 is calculated to be 28.4% with GD of −0.5 ns at f_0. Similarly, the proposed circuit maintains wide flat magnitude and GD responses without cascading two NGD circuits with slightly different center frequencies.[4,12] In addition, magnitude of S_{21} and NGD fractional bandwidth can be controlled by R_{isoh} and R_0. Moreover, the input and out termination ports are well matched with port impedance without any additional circuit matching.

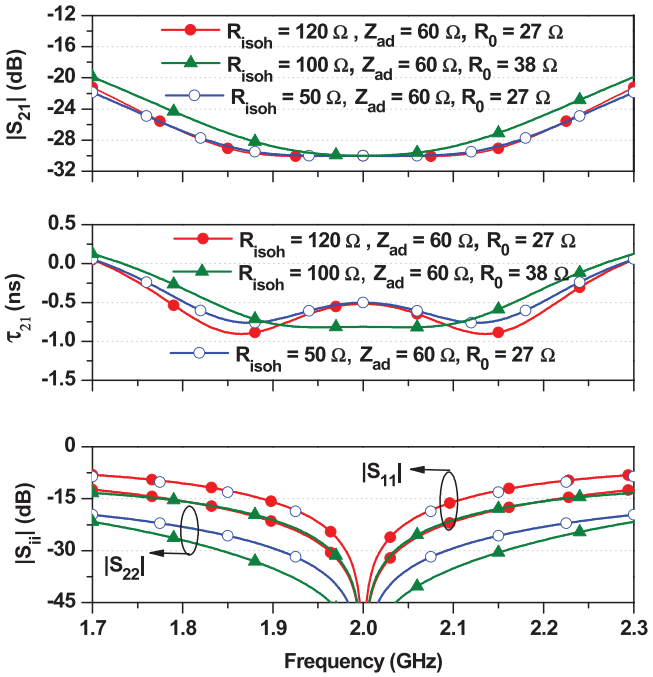

FIGURE 2 Calculated responses of proposed wideband NGD circuit with $R_a = 45\ \Omega$, $R_b = 55\ \Omega$, $k_h^2 = 1.032$, and $k_c^2 = 1.171$

Figure 3 depicts the GD and magnitude responses according to different power division ratios. In these results, the GD ripple is maintained within $\tau_{21} \pm 0.1$ ns around $f = f_0 = 2$ GHz. As seen from this figure, the higher NGD can be achieved when k_c^2 approaches toward k_h^2. Therefore, it is concluded that the proposed circuit can provide the arbitrary prescribed NGD by controlling power division ratios of 180° hybrid and in-phase combiner.

To show NGD performances of the proposed circuit in comparison with the state of art, Figure 4 shows comparison results of the GD, magnitude of $|S_{21}|$, and input/output return losses (S_{11}/S_{22}). For fair comparison, the NGD circuits are designed for GD = −1 ns and $|S_{21}| = -33.68$ dB at $f_0 = 2$ GHz. The simulation results of References 4, 17, 18 are obtained based on design method provided in these works. As observed from these results, the NGD characteristic of the proposed circuit shows two poles while the conventional circuits show only one pole. Similarly, Figure 4B shows the comparison results of $|S_{11}|$ and $|S_{22}|$. Although signal attenuation of work Reference 16 is smaller, the proposed NGD circuit provides the widest NGD bandwidth and magnitude flatness compared with the state of the art.[4,17,18] In addition, the magnitude of $|S_{11}|$ is very poor (< 0.2 dB) in case of Reference 18 as depicted in Figure 4B therefore, this circuit is not suitable for integrating with other circuits in practical applications.

For design graphs, the calculated GD, magnitude of S_{21}, and NGD FBW are shown in Figure 5 for different k_h^2, k_c^2, and GDs. In these calculations, the GD ripple is maintained within $\tau_{21} \pm 0.1$ ns at $f = f_0 = 2$ GHz. As observed from the graphs, the GD tends more negative value when k_c^2 approaches k_h^2. Additionally, the NGD fractional bandwidth and $|S_{21}|$ are decreased when GD becomes more negative. Therefore, a trade-off is required among NGD, fractional bandwidth, and insertion loss.

3 | SIMULATION AND EXPERIMENTAL RESULTS

For experimental proof of concept, the NGD circuit was fabricated at $f_0 = 2$ GHz using substrate with dielectric

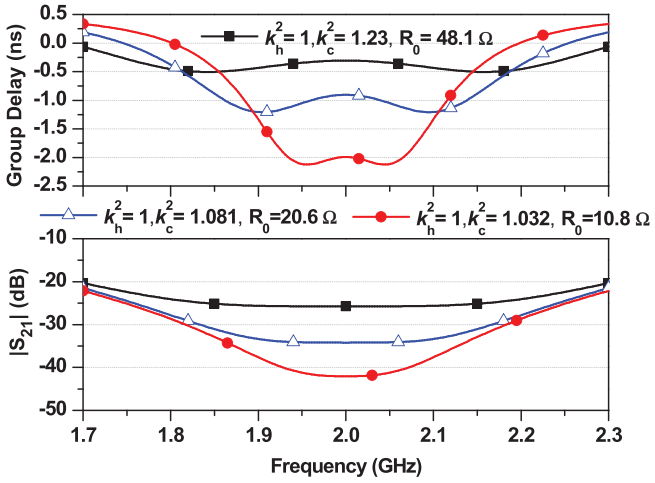

FIGURE 3 Calculated GD and magnitude responses of the proposed circuit according different power division ratios *with* $R_a = R_b = 50\ \Omega$, $Z_{ad} = 60\ \Omega$, and $R_{isoh} = 100\ \Omega$

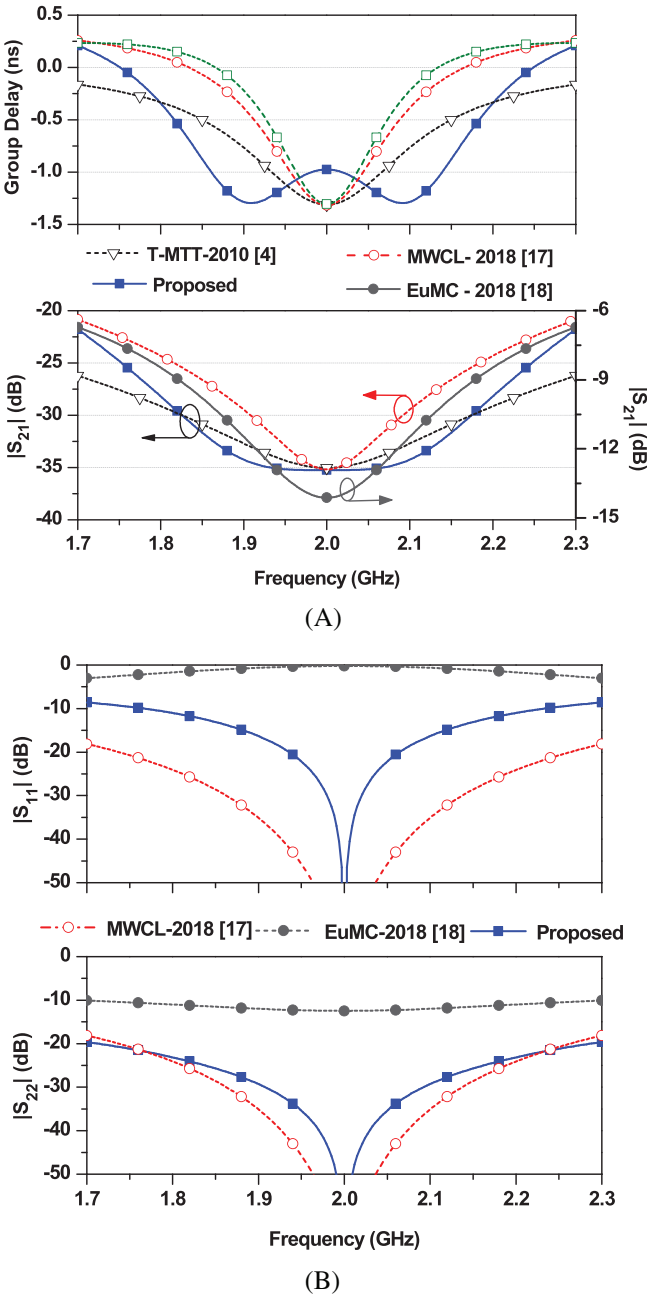

FIGURE 4 Comparison responses of proposed circuit with state of arts for same group delay and insertion loss: A, group delay/magnitude and, B, input/output return losses

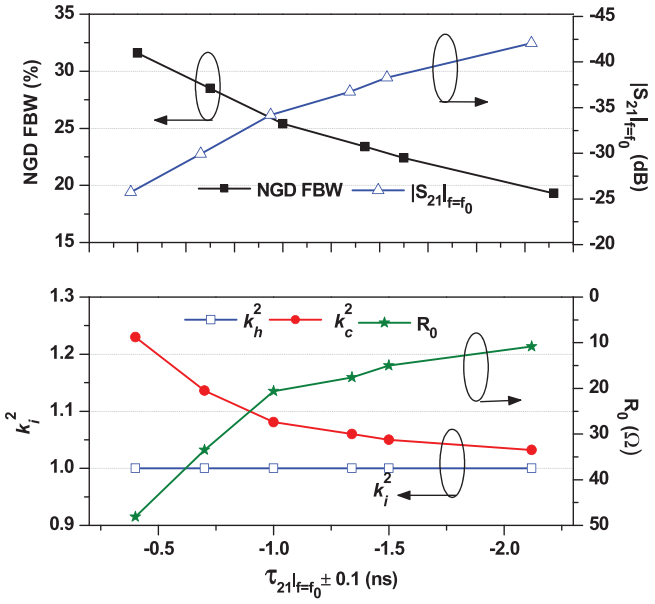

FIGURE 5 Calculated magnitude of S_{21}, NGD fractional bandwidth, power division ratios and R_0 according group delay variation with $f_0 = 2$ GHz, $R_a = R_b = 50\ \Omega$, $Z_{ad} = 60\ \Omega$, and $R_{isoh} = 100\ \Omega$

TABLE 1 Calculated circuit parameters of proposed NGD circuit with $R_a = R_b = 50\ \Omega$, $k_h^2 = 1$, $k_c^2 = 1.068$

Unit (Ω)					
Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
41.23	41.23	58.31	58.31	31.94	33.05
Z_7	Z_8	R_0	Z_{ad}	R_{isoh}	R_{isoc}
76.22	81.40	17	60	100	124.08

Abbreviation: NGD, negative group delay.

constant (ε_r) of 2.20 and thickness (h) of 0.787 mm. The design goal was to achieve a GD of −1 ns at f_0 with an assumption of termination port impedance $R_a = R_b = 50\ \Omega$. The termination port impedance of the designed circuit was chosen as 50 Ω for simplicity in measurement. The calculated circuit parameters for given specification are summarized in Table 1. The physical layout of the fabricated circuit is shown in Figure 6 with physical dimensions.

The simulated and measured results are shown in Figure 7. The measurement results are in good agreement with the simulations. A photograph of fabricated circuit is shown in Figure 7. From the measurement results, GD and $|S_{21}|$ are determined to be -0.88 ± 0.11 ns and − 33.63 dB, respectively. The NGD bandwidth is 460 MHz (FBW = 23%), providing the NGD-bandwidth product of 0.4048. The bandwidth of the magnitude flatness -33.12 ± 0.5 dB is 210 MHz. Similarly, flat-NGD

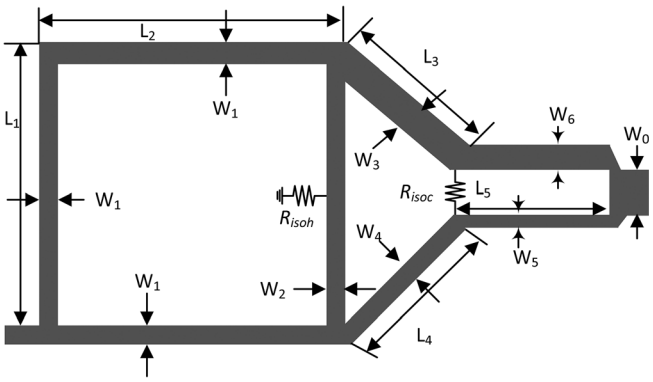

FIGURE 6 Physical layout of fabricated NGD circuit. Physical dimensions: $L_1 = 57.77$, $L_2 = 33.05$, $L_3 = 26.06$, $L_4 = 26.06$, $W_0 = 2.40$, $W_1 = 2.40$, $W_2 = 2.20$, $W_3 = 4.50$, $W_4 = 2.30$, $W_5 = 1$, $W_6 = 2.52$. (Unit: milimeter)

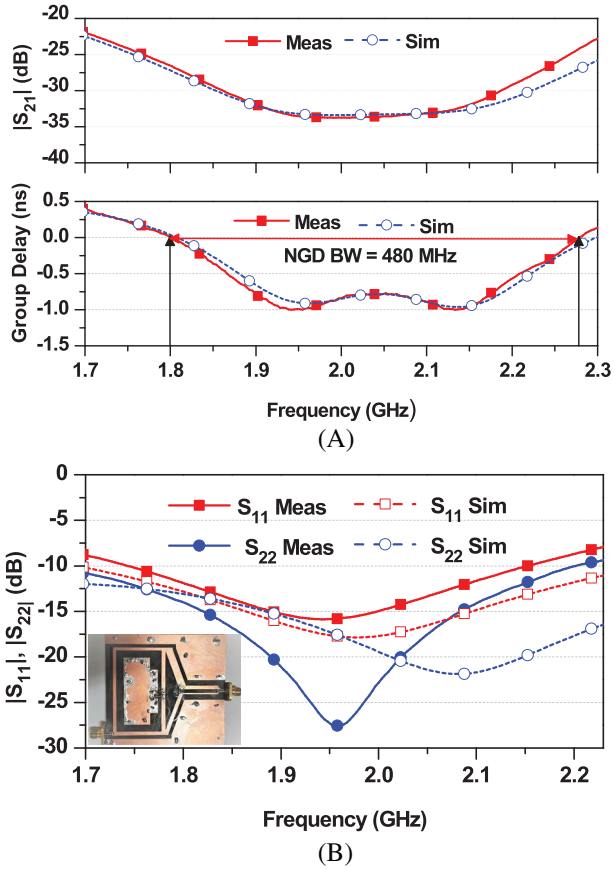

FIGURE 7 Simulated and measured results of fabricated circuit

bandwidth for 0.88 ± 0.11 ns GD fluctuation and 3-dB insertion loss bandwidth, which is defined as the 3-dB variation from center frequency insertion loss are 190 and 360 MHz, respectively. Table 2 shows the performances comparison of the proposed circuit with state-of-arts. Although overall size of the proposed circuit

TABLE 2 Performance comparison with state-of-arts

	Unit: GHz		$\tau_{21}\vert_{f_0}$	Unit: dB		
	f_0	BW	(ns)	$\vert S_{21}\vert$	RL	Size
12	1.96	0.40	−1.10	29.3	NA	$0.41\lambda_0 \times 0.51\lambda_0$
14	1	0.400	−1.50	39.8	20/20	$0.55\lambda_0 \times 0.15\lambda_0$
10	2.14	0.050	−1.03	3.82	30/30	$0.39\lambda_0 \times 0.39\lambda_0$
11	1	0.198	−1.58	32.5	23/23	$0.32\lambda_0 \times 0.13\lambda_0$
17	1.06	0.140	−2.09	18.1	25/33	$0.41\lambda_0 \times 0.41\lambda_0$
18	1	0.320	−0.82	15.7	0.5/5	$0.22\lambda_0 \times 0.24\lambda_0$
This	2	0.460	−0.88	33.1	18/22	$0.41\lambda_0 \times 0.51\lambda_0$

Abbreviations: BW, negative group delay bandwidth when GD < 0 ns; RL, input/output return losses.

($0.41\lambda_0 \times 0.51\lambda_0$) is slightly larger, the NGD bandwidth (GD < 0 ns) and magnitude flatness bandwidth are wider than the state of the art.[12-16] The measured input/output return losses are higher than 17.88 dB at f_0 and higher than 12 dB from 1.80 to 2.26 GHz.

4 | CONCLUSION

In this article, we theoretically and experimentally demonstrated a signal interference concept based on an arbitrary terminated wideband negative group delay circuit. In the proposed circuit, the negative group delay was generated by controlling the power division ratios of 180° hybrid and in-phase combiner. Additionally, the proposed circuit provides wideband flat magnitude and GD responses without cascading two negative group delay circuits with slightly different center frequencies. The experimental results showed that the negative group delay and magnitude flatness responses were widest among the state-of-arts.

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REFERENCES

1. Brillouin L, Sommerfeld A. *Wave Propagation and Group Velocity*. New York: Academic Press Network; 1960:113-137.
2. Soli D, Chiao RY. Superluminal effects and negative delays in electronics, and their application. *Phys Rev E Stat Phys Plasmas Fluids Relat Interdiscip Top*. 2002;5:566011-5661014.
3. Noto H, Yamauchi K, Nakayama M, Isota Y. Negative group delay circuit for feed-forward amplifier. *Proc of IEEE Inter Microwave Symp Dig*. 2007;1103-1106.
4. Choi H, Jeong Y, Kim CD, Kenney JS. Efficiency enhancement of feedforward amplifiers by employing a negative group delay circuit. *IEEE Trans Microw Theory Tech*. 2010;58(5):1116-1125.
5. Choi H, Jeong Y, Kim CD, Kenney JS. Bandwidth enhancement of an analog feedback amplifier by employing a negative group delay circuit. *Prog Electromagn Res*. 2010;105:253-272.
6. Mirzaei H, Eleftheriades GV. Realizing non-Foster reactive elements using negative group delay networks. *IEEE Trans Microw Theory Tech*. 2013;61(12):4322-4332.
7. Lucyszyn S, Robertson ID, Aghvami AH. Negative group delay synthesizer. *Electron Lett*. 1993;29(9):798-800.
8. Ravelo B, P´erennec A, Roy ML, Boucher YG. Active microwave circuit with negative group delay. *IEEE Microw Wireless Compon Lett*. 2007;17(12):861-863.
9. Lucyszyn S, Robertson ID. Analog reflection topology building blocks for adaptive microwave signal processing applications. *IEEE Trans Microw Theory Tech*. 1995;43(3):601-611.
10. Chaudhary G, Jeong Y. Negative group delay phenomenon analysis using finite unloaded quality factor resonators. *Prog Electromagn Res*. 2016;156:55-62.
11. Shao T, Fang S, Wang Z, Liu H. A compact dual-band negative group delay microwave circuit. *Radio Eng*. 2018;27:1070-1076.
12. Chaudhary G, Jeong Y. Low signal attenuation negative group delay network topologies using coupled lines. *IEEE Trans Microw Theory Tech*. 2014;62(10):2316-2324.
13. Jeong Y, Choi H, Kim CD. Experimental verification for time advancement of negative group delay in RF electronics circuits. *Electron Lett*. 2010;46(4):306-307.
14. Chaudhary G, Jeong Y. A design of compact wideband negative group delay network using cross coupling. *Microw Opt Technol Lett*. 2014;56(11):2612-2616.
15. Chaudhary G, Jeong Y, Lim J. Microstrip line negative group delay filters for microwave circuits. *IEEE Trans Microw Theory Tech*. 2014;62(2):234-243.

16. Michael Wu CT, Itoh T. Maximally flat negative group delay circuit: a microwave transversal filter approach. *IEEE Trans Microw Theory Tech*. 2014;6(6):1330-1342.
17. Wang Z, Cao Y, Shao T, Fang S, Liu Y. A negative group delay microwave circuit based on signal interference techniques. *IEEE Microw Wireless Compon Lett*. 2018;28(4):290-292.
18. Sanchez-Soriano, M. A., Dura, J., Sirci, S., and Marini, S., Signal-interference based structure with negative group delay properties. Paper presented at: Proceedings of 48th European Microwave Conference, 2018, pp.1021–1024.
19. Ahn H, Wolf I, Chang I. Arbitrary terminations, arbitrary power division, and small-sized ring hybrids. *IEEE Trans Microw Theory Tech*. 1997;45:2241-2247.

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