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Planar Tunable Negative Group Delay Circuit with Low Reflection Loss

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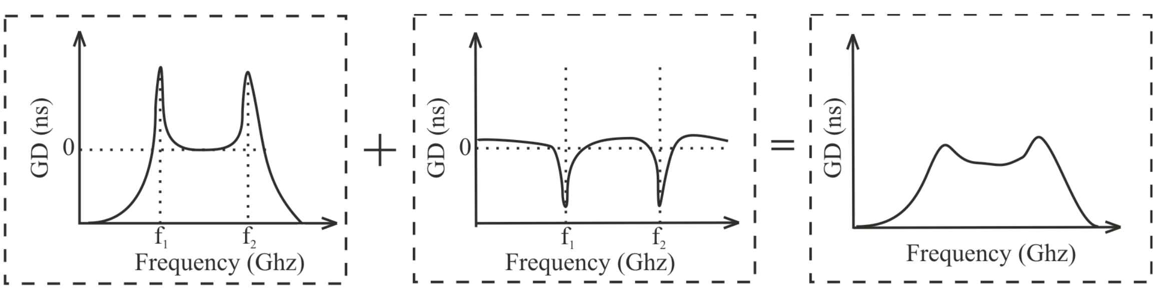
Abstract—This paper presents the design of a planar tunable Negative Group Delay (NGD) circuit with low reflections. A pulse-shaped stub inscription on the signal strip of a microstrip line generates a negative group delay, which can then be tuned to a desired value by varying the resistance inside the inscription. Poor reflection characteristics are inherent in such circuits, and a conventional solution like a simple impedance matching circuit compromises the overall NGD performance for a reduced reflection loss. Here, we have included a novel impedance-matching network loaded with absorptive elements at the input/output ports to avoid any reflections from the circuit, while maintaining its NGD behavior and compactness. The measured results validate the proposed design with -5 ns GD at 3 GHz with less than -10 dB reflection loss over the whole NGD bandwidth of 228 MHz at 3 GHz.

1. INTRODUCTION

Flat amplitude response and linear phase characteristics are critical requirements for distortionless transmission in communication systems. However, these conditions are quite challenging to attain due to system imperfections. Hence, Group Delay (GD) equalization has become necessary to compensate for the phase distortions arising in the system. A bandpass filter, an essential component in a wireless communication system, can generate a nonlinear phase response with Positive Group Delay (PGD) peaks at the edges of their passband frequency response (Fig. 1(a)). Negative Group Delay (NGD) networks are a straightforward solution to compensate for these undesirable phase response peaks without deteriorating the overall GD (Figs. 1(b) and (c)). PGD is the time delay of the signal in



(a) Bandpass filter (b) NGD circuit (c) Phase corrected circuit

Figure 1. GD equalization in bandpass filter using NGDC [1].

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reaching the output, which implies that in the case of NGD, the signal reaches the output in time advancement, or in other words, such circuits try to predict the input. However in reality, an NGD circuit only reshapes the input signal so that the output reaches its peak value before the input reaches its peak. This unusual phenomenon, which happens without violating Einstein's theory of relativity, is known as the super-luminal group velocity and occurs only for a band-limited signal.

Lucyszyn et al. [2] demonstrated the first NGD Microwave Integrated Circuit (MIC) synthesizer operating at 1 GHz utilizing an RLC-tuned circuit. The circuit used a Lange coupler and cold Field Effect Transistors (FETs) implemented as variable resistors and varactor diodes as variable capacitors. The circuit generated high NGD values within narrow bandwidths but incurred high transmission losses in the pass band. Ravelo et al. [3] implemented an active NGD topology with a series RLC network shunt cascaded with a FET. Further, using this active NGD topology, they implemented a broadband balun [4]. They investigated the applicability of such active NGD topologies in the design of constant phase shifters over a broad bandwidth [5] and demonstrated a frequency-independent phase shifter with a constant transmission phase [6].

Another application that utilizes an NGDC is in the performance enhancement of feed-forward amplifiers. Noto et al. [7] used three resonators with resistors and shortened delay lines (40% short) to increase the feedforward amplifier efficiency from 9% to 12%. Nevertheless, the reported circuit has high reflections at its input/output ports and narrow signal bandwidth, making it unsuitable for practical linear power amplifier systems used for wide-band modulated signals. Choi et al. [8] overcome these limitations with a two-stage reflection-type NGDC based on a transmission line resonator derived from a lumped element equivalent circuit.

NGDC topologies based on lumped element resonators are challenging to implement at microwave frequencies and for high-speed system integration. Consequently, NGDCs are designed with periodic structures such as Defected Microstrip Structures (DMSs) and Defected Ground Structures (DGSs). Chaudhary et al. [9] etched a U-shaped pattern on the ground plane functioning as a DGS, which, when being loaded with an external resistor, resulted in a GD of -4.6 ns at 3.5 GHz suitable for Worldwide Interoperability for Microwave Access (WiMax) applications. Similarly, a U-shaped slit on the signal strip of a microstrip line functioning as a DMS, along with an external capacitor and resistor combination, is reported to have produced a GD of -7 ns at 2.14 GHz suitable for WCDMA applications [10]. The authors themselves have proposed a DMS-based compact tunable NGDC with GD tunability and frequency switchability in [11], which utilizes a variable resistor to control the NGD as required. However, the reported NGD topologies [9–11] suffer from poor reflection characteristics. It is imperative to design NGDCs with good input/output matching to avoid loading effects and the losses incurred due to the reflections. Hybrid couplers, impedance transformers, and power dividers/combiners have been utilised for NGDCs with low reflections, but they often involve a tradeoff [12–18].

In this paper, we have proposed a pulse-shaped stub-loaded microstrip line-based compact NGDC design. It includes impedance-matching networks loaded with absorptive elements at the input/output ports to avoid any reflections from the circuit without compromising its NGD performance. The following sections discuss its design, results, and performance comparison with similar NGDCs reported recently.

2. PROPOSED CIRCUIT

As discussed, NGDCs can compensate for the PGDs introduced by the bandpass filters used in the RF front end of a communication system and hence can ensure a distortion-less transmission. However, when such circuits are cascaded with filters, the input/output reflections in the NGDC lead to performance degradation. In [11], we presented a compact pulse-shaped stub-loaded NGD generator with GD tunability (Fig. 2). A simple pulse shape inscribed in a microstrip line generates a -5.5 ns GD at 3 GHz along with band-stop characteristics, and a resistor R controls the GD. However, the circuit suffers from a high reflection coefficient at its input/output ports (around -1.4 dB). The performance degradation that can happen by placing such circuits in line with other sensitive circuits in the RF front end makes it essential to modify the design to bring the reflections down while maintaining the circuit's compact geometry and desirable GD performance. The following section presents the design of a compact pulse-shaped stub-loaded NGDC with low reflections at its input/output ports.

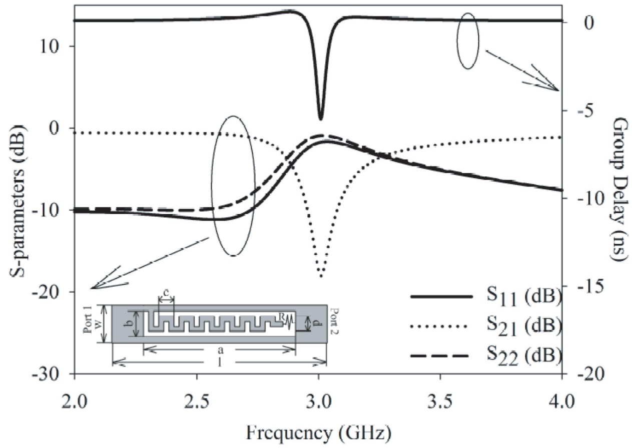
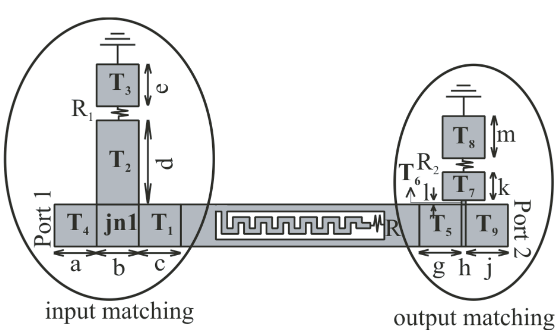


Figure 2. S-parameters and GD characteristics of pulse-shaped stub-loaded NGDC with its top view where $l = 17\,\text{mm}$, $w = 3\,\text{mm}$, $a = 12\,\text{mm}$, $b = 2\,\text{mm}$, and $c = d = 1.2\,\text{mm}$.

2.1. Design, Results, and Discussions

NGD generator circuits have a band-stop feature with a finite attenuation over the narrow frequency band at which the NGD is generated (Fig. 2). However, high reflections (S_{11} and S_{22}) in the stopband lead to performance degradation of the other devices cascaded with the circuit. Balanced-type hybrid structures are one of the solutions to reduce such reflections, but they increase the overall circuit size [12]. Another solution that does not significantly increase the circuit size is using impedance transformers at the input and the output. However, such matching circuits will not only reduce the reflection coefficient but also reduce the signal attenuation and, in turn, reduce the NGD. An alternative is to include absorptive elements [19] in the input/output matching circuits that could absorb the undesired signal reflections at the stopband while retaining the band-stop filter feature of the NGDC.

In this paper, we have proposed a transmission line-based matching circuit with an absorptive element at Ports 1 and 2 of the circuit in Fig. 2. Fig. 3(a) shows the proposed design with low



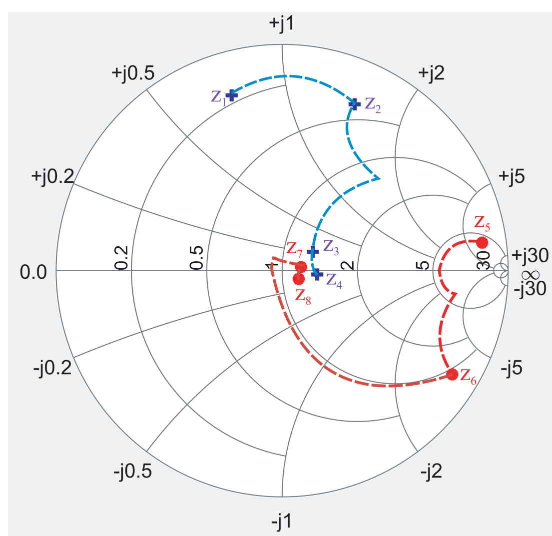


Figure 3. Proposed low-loss pulse-shaped stub-loaded NGDC with its (a) Top view where $a = b = c = e = g = j = m = 3\,\text{mm}$, $d = 6\,\text{mm}$, $h = l = 0.3\,\text{mm}$ and $k = 2\,\text{mm}$, (b) Transition of input/output port impedance.

input/output reflections. The lengths and widths of the transmission lines of the matching circuits are designed as shown in Fig. 3(b). The blue cross points (Z_1, Z_2, Z_3, and Z_4) in Fig. 3(b) show the impedance transition from Port 1 as each stub is cascaded to the pulse-shaped stub-loaded NGDC. Z_1 denotes the input impedance of the pulse-shaped stub-loaded NGDC at 3 GHz, and as we add a series stub T_1, Z_1 shifts to Z_2. Then, adding a short stub T_2 and grounding it through a resistor R_1 of 150 Ω, the impedance shifts to Z_3. The resistor acting as the absorptive element absorbs the reflections from the input of the pulse-shaped stub-loaded NGDC. Similarly, an absorptive impedance matching circuit is designed at Port 2 of the NGDC. The red dot points (Z_5, Z_6, Z_7, and Z_8) in Fig. 3(b) show that the impedance transition as each stub is connected to Port 2.

Figure 4(a) shows the effects of matching circuits loaded with and without the absorptive elements R_1 and R_2. It clearly shows that a simple input/output matching circuit reduces the reflections but deteriorates the bandstop behaviour due to a higher transmission coefficient (S_{21}). However, the presence of the resistors in the matching circuit prevents reflections while maintaining the signal attenuation feature required to generate NGD. The circuit has a tunable GD feature by varying the resistor, R, placed inside the pulse-shaped inscription, and Fig. 4(b) shows that the proposed circuit has its GD tunability varying from −0.1 ns to −5 ns as the resistance tunes from 1 kΩ to 1 MΩ while maintaining the reflections below −10 dB over the NGD bandwidth.

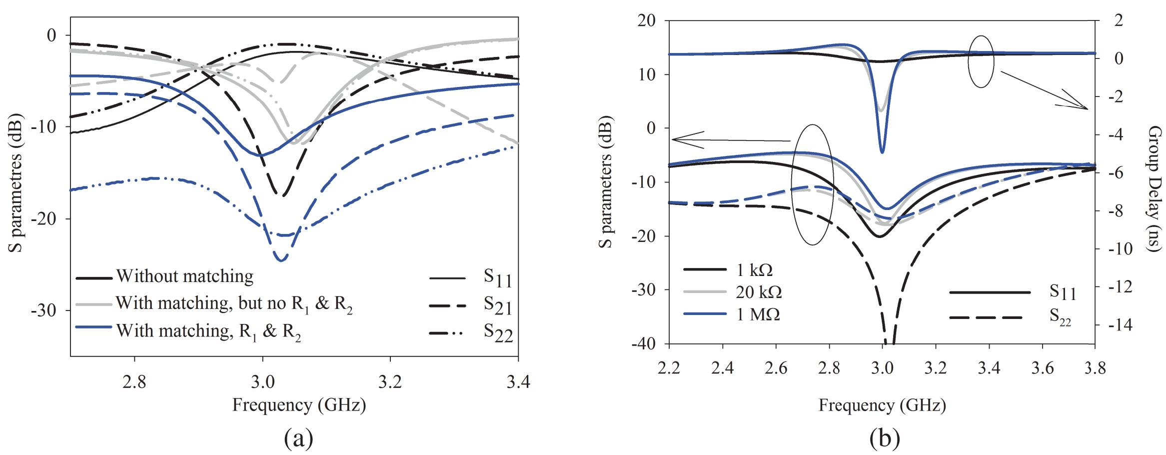


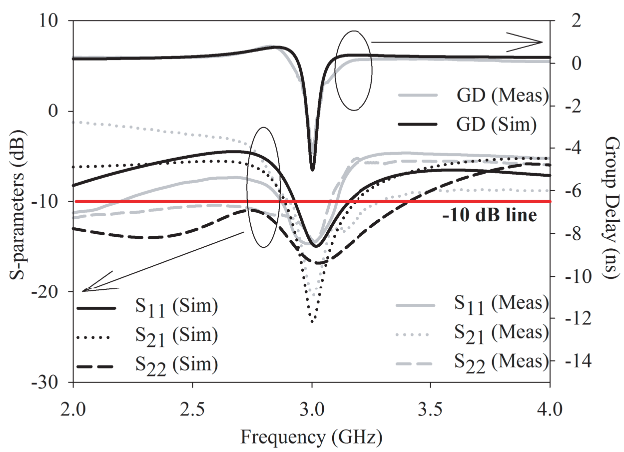
Figure 4. (a) Effect of R_1 and R_2 on S parameter characteristics. (b) S-parameters and GD characteristics of Low loss pulse-shaped stub-loaded NGDC for varying R.

The proposed design (that generates −5 ns GD at 3 GHz with 128 MHz NGD bandwidth) is fabricated in Fig. 5(b) and measured. The results (Fig. 5(a)) confirm that it generates −4.23 ns NGD at 3 GHz with 228 MHz NGD bandwidth and has reduced reflections at its ports, which agrees reasonably well with the simulated results. The minor deviations in the measured results from the fabricated ones could be due to the fabrication uncertainties arising while soldering SMD resistors, SMA connectors, and irregularities in etching, etc.

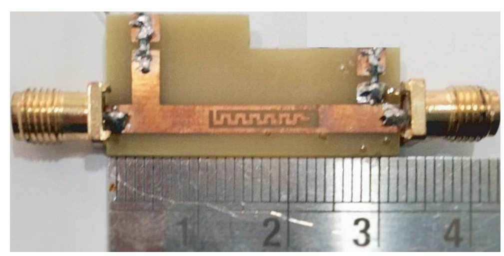
Table 1 compares the proposed compact NGDC design with low reflections with similar designs recently reported in terms of NGD, return loss at input/output ports, NGD bandwidth (BW), circuit size and tunability (T). [12–18] discuss NGD circuits with low reflections but with lower NGD bandwidth and no GD tunability. Among them, [13] presents a larger microstrip line-based NGD network using impedance transformers to lower the reflections, whereas [12] uses a balanced type hybrid structure consisting of two 90° hybrid couplers to improve the return loss characteristics of the DMS-based transmission type NGD network. Utilizing DMS topology in [12] and impedance transformers in [13], our proposed circuit generates NGD with low losses. The signal interference technique in [14] composing two Wilkinson power dividers and a coupled line phase shifter generates only −2 ns GD at 1 GHz with matching at the input/output ports. Wan et al. [15] propose a fully distributed NGD circuit comprising a three-port power divider and a power combiner connected by a four-port coupled line that produces

Table 1. Comparison with similarly reported literature.

Ref (year)	Freq (GHz)	GD (ns)	S_{11} (dB)	S_{22} (dB)	BW (MHz)	Size ($\lambda_g \times \lambda_g$)	T	$BW_{3\,\mathrm{dB}}$
[13] (2014)	1.96	-6.5	-34	-37	100	0.7×0.7	No	-
[12] (2014)	2.125	-8.2	-28	-19	40	0.7×0.3	No	-
[14] (2018)	1.016	-2.09	-45	-33	144	0.4×0.4	No	-
[15] (2020)	1.2	-2.8	-15	-13	30	0.5×0.3	No	-
[16] (2021)	1.89	-1	-15	-	20	1.16×0.6	No	-
[17] (2021)	1.2/3.5 5.8	$-1.1/-1.2/$ -1.1	$-16/-24/$ -18.9	$-16/-24/$ -18.9	149/301/ 208	0.34×0.6	No	-
[18] (2022)	1.5/2.4/ 3.4/4.2	$-1.8/-1.6/$ $-1.4/-0.9$	$-15/-11/$ $-11/-10$	$-15/-11/$ $-11/-10$	23/40/ 51/69	0.9×0.5	No	-
[20] (2019)	2.8/4.3/ 5.8	$-6.5/-5.4/$ -3	> -10	> -10	120/180/ 250	0.34×0.6	Yes	-
[21] (2020)	2.14	-0.5 to -2.2	< -10	< -10	90 to 50	0.5×0.2	Yes	-
This work	3	0 to -5	< -10	< -10	128 to 228	0.7×0.3	Yes	50 to 195



(a)



(b)

Figure 5. (a) S-parameters and GD characteristics of Low loss pulse-shaped stub-loaded NGDC and (b) Fabricated prototype.

a low NGD value of -2.8 ns at 1.2 GHz with less reflections. The same authors recently developed another low-loss distributed NGDC [16] consisting of a reverse T-stub with two coupled lines and two transmission lines that achieve only -1 ns GD with low reflection loss. The self-matched triband circuit in [17] consisting of three-stage transmission lines connected with resistors operates for three bands. Similarly, the circuit in [18] consists of a crossed resonator combined with a coupled line, achieving low attenuation and reflections. Unlike the previous circuit in [17], the circuit has no lumped elements and generates NGD at four bands. However, the NGD circuits in [20, 21] have better control over their GD, wherein [20] uses resistors, and [21] uses a resistor connected to a PIN diode to achieve GD tunability. In comparison, our proposed work generates a better range of tunable GD of 0 to -5 ns at 3 GHz with good NGD bandwidth. In this paper, NGD BW denotes the bandwidth over which the group delay is negative. Simultaneously, this achieved bandwidth is almost inside the 3-dB variations from the minimum of S_{21}. Therefore, Table 1 summarises the NGD BW within the 3 dB variations (denoted as

$BW_{3\,\mathrm{dB}}$) from S_{21} minimum for our proposed work. Hence, distortion appearing at the output pulse does not occur, as mentioned in [22, 23]. Moreover, the circuit size is relatively compact, with lower reflections at the input/output ports.

3. CONCLUSION

This paper presents the design of a tunable planar NGD circuit with a pulse-shaped stub-loaded DMS topology with low reflections. Though a design based on a simple pulse-shaped inscription on a microstrip line generates -5.5 ns GD at 3 GHz, it causes reflections at the input/output ports. However, designing matching networks at the input/output ports of the circuit lowers the reflections but reduces the signal attenuation, leading to a decrease in NGD. Hence, matching circuits with stubs loaded with absorptive elements are designed and connected at the input/output ports of the NGD circuit to lower the reflection losses below -10 dB while maintaining the NGD performance. In addition, the proposed circuit design also has a resistor connected to the inscription, enabling better control over the generated NGD. The fabricated prototype validated the design. Compared with similar designs reported in the literature, it is seen that our proposed circuit is compact and GD tunable with low reflections throughout its GD tunability range.

REFERENCES

1. Su, Y., "Group delay variations in microwave filters and equalization methodologies," Department of Microtechnology and Nanoscience, Master's Thesis in Microtechnology and Nanoscience, 2012.
2. Lucyszyn, S., I. D. Robertson, and A. H. Aghvami, "Negative group delay synthesizer," *Electron. Lett.*, Vol. 29, 798–800, 1993.
3. Ravelo, B., A. Pérennec, M. Le Roy, and Y. G. Boucher, "Active microwave circuit with negative group delay," *IEEE Microwave and Wireless Components Letters*, Vol. 17, No. 12, 861–863, Dec. 2007.
4. Ravelo, B., A. Pérennec, and M. Le Roy, "Broadband balun using active negative group delay circuit," *Eur. Microwave Conf.*, 466–469, 2007.
5. Ravelo, B., M. Le Roy, and A. Pérennec, "Application of negative group delay active circuits to the design of broadband and constant phase shifters," *Microw. Opt. Technol. Lett.*, Vol. 50, 3078–3080, 2008.
6. Ravelo, B., A. Pérennec, and M. Le Roy, "Synthesis of frequency-independent phase shifters using negative group delay active circuit," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 21, No. 1, 17–24, Wiley, 2011.
7. Noto, H., K. Yamauchi, M. Nakayama, and Y. Isota, "Negative group delay circuit for feed-forward amplifier," *2007 IEEE/MTT-S International Microwave Symposium*, 1103–1106, 2007.
8. Choi, H., Y. Kim, Y. Jeong, and C. D. Kim, "Synthesis of reflection type negative group delay circuit using transmission line resonator," *2009 European Microwave Conference (EuMC)*, 902–905, 2009, doi: 10.23919/EUMC.2009.5296195.
9. Chaudhary, G., J. Jeong, P. Kim, Y. Jeong, and J. Lim, "Compact negative group delay circuit using defected ground structure," *2013 Asia-Pacific Microwave Conference Proceedings (APMC)*, 22–24, 2013.
10. Chaudhary, G., Y. Jeong, and J. Lim, "Miniaturized negative group delay circuit using defected microstrip structure and lumped elements," *2013 IEEE MTT-S International Microwave Symposium Digest (MTT)*, 1–3, 2013.
11. Palson, C. L., R. K. Sreelal, D. D. Krishna, and B. R. Jose, "Frequency switchable and tunable negative group delay circuits based on defected microstrip structures," *Progress In Electromagnetics Research M*, Vol. 113, 23–33, 2022.
12. Chaudhary, G., Y. Jeong, and J. Lim, "Realization of negative group delay network using defected microstrip structure," *International Journal of Antennas and Propagation*, Vol. 2014, 1–5, 2014.

13. Chaudhary, G., Y. Jeong, and J. Lim, "Microstrip line negative group delay filters for microwave circuits," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 62, No. 2, 234–243, Feb. 2014.
14. Wang, Z., Y. Cao, T. Shao, S. Fang, and Y. Liu, "A negative group delay microwave circuit based on signal interference techniques," *IEEE Microwave and Wireless Components Letters*, Vol. 28, No. 4, 290–292, Apr. 2018.
15. Wan, F., N. Li, B. Ravelo, and J. Ge, "O=O shape low-loss negative group delay microstrip circuit," *IEEE Transactions on Circuits and Systems II: Express Briefs*, Vol. 67, No. 10, 1795–1799, Oct. 2020.
16. Wan, F., N. Li, B. Ravelo, W. Rahajandraibe, and S. Lalléchère, "Design of =I= shape stub-based negative group delay circuit," *IEEE Design* & *Test.*, Vol. 38, No. 2, 78–88, Apr. 2021.
17. Meng, Y., Z. Wang, S.-J. Fang, and H. Liu, "A tri-band negative group delay circuit for multiband wireless applications," *Progress In Electromagnetics Research C*, Vol. 108, 159–169, 2021.
18. Gu, T., J. Chen, B. Ravelo, F. Wan, V. Mordachev, and Q. Ji, "Quad-band NGD investigation on crossed resonator interconnect structure," *IEEE Transactions on Circuits and Systems II: Express Briefs*, Vol. 69, No. 12, 4789-4793, 2022.
19. Lu, Q., X. Wu, and C. Wang, "Compact broadband absorptive bandstop filter based on microstrip," *Journal of Physics: Conference Series*, Vol. 1651, No. 1, 012104, 2020.
20. Xiao, J.-K. and Q.-F. Wang, "Individually controllable tri-band negative group delay circuit using defected microstrip structure," *2019 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, 1–3, 2019.
21. Girdhari, C. and J. Yongchae, "Reconfigurable negative group delay circuit with a low insertion loss using a coupled line," *J. Electromagn. Eng. Sci.*, Vol. 20, No. 1, 73–79, 2020, https://www.jees.kr/journal/view.php?number=3374.
22. Macke, B., B. Ségard, and F. Wielonsky, "Optimal superluminal systems," *Phys. Rev. E*, Vol. 72, 035601(R), 1–4, Sep. 2005.
23. Kandic, M. and G. Bridges, "Negative group delay prototype filter based on cascaded second order stages implemented with Sallen-Key topology," *Progress In Electromagnetics Research B*, Vol. 94, 1–18, 2021.