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EuMC/EuMIC07 **CMOS and BiCMOS Solutions for RF and Millimetre-Wave PA** Chair: Eric Kerhervé, University of Bordeaux Co-Chair: Baudouin Martineau, STMicroelectronics	**EuMC01** **Focus Session on 3D/ Additive and Inkjet-Printed RF Components, Modules and Large-Area 'Smart Skins and Antenna Arrays'** Chair: Manos Tentzeris, Georgia Tech Co-Chair: Luca Roselli, Università di Perugia	**EuMC02** **Transmission Lines and New Technologies** Chair: Marco Dionigi, University of Perugia Co-Chair: Cristiano Tomassoni, University of Perugia	**EuMC03** **Reconfigurable and Multi-Band Antennas** Chair: Jozef Modelski, Warsaw Univerity of Technology Co-Chair: Christian Waldschmidt, University of Ulm	
EuMC/EuMIC07-01 ***A Broadband 75 to 140 GHz Amplifier in 0.13-µm SiGe HBT Process*** P. Ho[1], Y. Lin[1], H. Wang[1], C. Meliani[2], [1]National Taiwan University, Taipei, Taiwan, [2]IHP Microelectronics, Frankfurt, Germany	***EuMC01-01*** ***Novel Inkjet Printed Modules for Sensing, Radar and Energy Harvesting Applications*** A. Traille[1], S. Kim[2], A. Coustou[1], H. Aubert[1], M. M. Tentzeris[2], J. Kimionis[2], A. Georgiadis[3], A. Collado[3], [1]Laboratoire d'Analyse et d'Architecture des Systemes, Toulouse, France, [2]Georgia Institute of Technology, Atlanta, United States, [3]CTTC, Castelldefels, Spain	***EuMC02-01*** ***Non-Uniform C-Section Phasers for Enhanced Design Flexibility in Radio Analog Signal Processing*** S. Taravati[1], Q. Zhang[2], C. Caloz[1], [1]Ecole Polytechnique de Montreal, Montreal,, Canada, [2]South University of Science and Technology, Shenzhen, China	***EuMC03-01*** ***Frequency Tunable Patch Antenna with Electrically Actuated Supported Polymer Membrane*** S. Baron[1], B. Guiffard[1], A. Sharaiha[2], [1]Université de Nantes, IETR, UMR 616[4], Nantes, France, [2]Université de Rennes[1], IETR, UMR 616[4], Rennes, France	09:00h - 09:20h
EuMC/EuMIC07-02 ***5-GHz Band SiGe HBT Linear Power Amplifier IC With Novel CMOS Active Bias Circuit For WLAN Application*** X. Yang[1], T. Sugiura[2], N. Otani[2], T. Murakami[2], E. Otobe[2], T. Yoshimasu[1], [1]Waseda University, Kitakyushu, Japan, [2]Samsung R&D Institute Japan, Yokohama, Japan	***EuMC01-02*** ***Inkjet-Printed Reflection Amplifier for Increased-Range Backscatter Radio*** J. Kimionis[1], A. Georgiadis[2], A. Collado[2], M. M. Tentzeris[1], [1]Georgia Institute of Technology, Atlanta, United States, [2]Centre Tecnologic de Telecommunicacions de Catalunya, Castelldefels, Spain	***EuMC02-02*** ***Coupled Line Negative Group Delay Circuits With Very Low Signal Attenuation and Multiple-Poles Characteristics*** G. Chaudhary[1], P. Kim[1], J. Kim[1], Y. Jeong[1], J. Lim[2], [1]Chonbuk National University, Jeonju-si, Republic of Korea, [2]Soonshunhyang University, Asan, Republic of Korea	***EuMC03-02*** ***Design of a Compact Wideband Slot Antenna Using Parasitic Reactive Tuning*** K. Naishadham, Georgia Institute of Technology, Atlanta, United States	09:20h - 09:40h
EuMC/EuMIC07-03 ***A K-Band Power Amplifier with Adaptive Bias in 90-nm CMOS*** J. Liu, C. Chan, S. S. Hsu, National Tsing Hua University, Hsinchu, Taiwan	***EuMC01-03*** ***A Metamaterial-Inspired Temperature Stable Inkjet-Printed Microfluidic-Tunable Bandstop Filter*** W. Su[1], C. Mariotti[2], B. S. Cook[1], S. Lim[3], L. Roselli[2], M. M. Tentzeris[1], [1]Georgia Institute of Technology, Atlanta, United States, [2]University of Perugia, Perugia, Italy, [3]Chung-Ang University, Seoul, Republic of Korea	***EuMC02-03*** ***Broadband Monolithic Left-Handed Coupled-Lines Incorporating Interwoven Capacitor and Stacking Inductor*** G. Li, H. Wu, C. C. Tzuang, Tianjin University, Tianjin, China	***EuMC03-03*** ***A Frequency and Polarization Reconfigurable Patch Antenna at K-Band*** B. Rohrdantz, C. Luong, A. F. Jacob, Techn. Univ. Hamburg-Harburg, Hamburg, Germany	09:40h - 10:00h
EuMC/EuMIC07-04 ***Transformer Based Dual-Power-Mode CMOS Power Amplifier for Handset Applications*** Y. Cho[1], B. Park[1], S. Jin[1], J. Kim[1], K. Moon[1], D. Kang[2], H. Jin[1], S. Koo[1], B. Kim[1], [1]Pohang University of Science and Technology (POSTECH), Pohang, Republic of Korea, [2]Broadcom Corporation, Matawan, United States	***EuMC01-04*** ***Inkjet-Printed Elastomeric Millimeter-Wave Devices*** S. Pacchini[1,2], S. Hage-Ali[3], A. Togonal[1,2], N. Tiercelin[3], P. Pernod[3], P. Coquet[1,2,3], [1]Cintra CNRS/NTU/THALES UMI 328[8], Singapore, Singapore, [2]Nanyang Technological University, Singapore, Singapore, [3]IEMN UMR Cnrs 8520, Villeneuve d'Ascq, France	***EuMC02-04*** ***Crosstalk in Substrate Integrated Waveguides: a Semi-Analytical Approach based on Side Leakage*** M. Pasian, M. Bozzi, L. Perregrini, University of Pavia, Pavia, Italy	***EuMC03-04*** ***A Compact and Reconfigurable Beam Pattern ESPAR Antenna with Automatic Impedance Matching System*** S. Yoo, K. Kim, T. Yeo, S. Lee, D. Lee, J. Yu, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea	10:00h - 10:20h
	EuMC01-05 ***Wireless Power Transmission Based on Resonant Electrical Coupling*** R. D. Fernandes, J. N. Matos, N. B. Carvalho, Instituto de Telecomunicações, Aveiro, Portugal	***EuMC02-05*** ***Broadside-Coupled Multi-Octave Impedance Transformer*** Z. Zhang[1], G. Boeck[1,2], [1]Berlin Institut of Technology, Berlin, Germany, [2]Leibniz-Institut fuer Hoechstfrequenztechnik, Berlin, Germany	***EuMC03-05*** ***Substrate Integrated Waveguide Cavity Backed Slot Antenna for Dual-Frequency Application*** S. Mukherjee, A. Biswas, K. V. Srivastava, Indian Institute of Technology, Kanpur, India	10:20h - 10:40h

Coupled Line Negative Group Delay Circuits With Very Low Signal Attenuation and Multiple-poles Characteristics

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***Abstract*—This paper presents a novel design of negative group delay circuit (NGDC) with very low signal attenuation (SA) and multiple-poles in group delay (GD) characteristics. The very low SA is obtained due to high characteristics of coupled lines. Theoretical analysis shows that the multiple-poles in GD characteristics can provide wider negative GD bandwidth and be obtained by connecting coupled lines resonators with slightly different center frequencies separated by quarter-wavelength transmission lines. For experimental validation, the NGDCs with 2-poles and 3-poles in GD characteristics are designed, simulated, and measured. The measurement results have a good agreement with theoretical predictions.**

Keywords*—*Coupled lines, low signal attenuation, negative group delay.

I. Introduction

It was theoretically proven that abnormal group velocity which includes the negative group delay (NGD) can occur at same range of frequencies when absorption or signal attenuation (SA) is maximum [1]. The experimental result of NGD has then verified in electronic circuit using bandpass amplifiers at very low frequency [2]. The NGD implies time advancement (not delay) in propagation, however, it does not violet the causality, since initial transient pulse is still limited to the front velocity, which will never exceed speed of light [1], [2].

Since the concept of NGD was proven theoretical in electronic circuitry, various works have been performed to design NGD networks at microwave frequencies [3]-[5]. The interesting characteristics of NGD networks have been applied to various practical applications in communication systems, such as the shortening or reducing delay lines, efficiency enhancement of feedforward linear amplifier, bandwidth enhancement of feedback linear amplifier, and beam-squint minimization in phased array antenna systems [3]-[5]. Recently, new and interesting applications of NGD networks have been reported in the realization of non-Foster reactive elements such as negative capacitances or inductances [6]. They have opened doors for new application fields of NGD networks, such as increasing the capacitance tuning range in a varactor diode [7], or enhancing the efficiency of class-E power amplifier by using negative capacitance to compensate the stray capacitance of transistor [8]. It can also be extended to electromagnetic applications, such as the increasing bandwidth of artificial magnetic conductor by loading with NGD networks as non-Foster elements [9].

The conventional passive NGD networks suffer from the excessive SA (up to 35 dB for a group delay (GD) of -8 ns) which can cause serious stability issues when NGD network is integrated with RF systems such as the power amplifier linearization system. Therefore, for the same differential-phase GD, the passband SA is expected to be as small as possible.

There are a few works have performed to reduce the SA of NGD networks. In [10], a composite NGD network with lower SA was presented. However, this circuit requires parallel lumped elements (such as an inductor, capacitor, and resistor) between two transmission lines (TLs). The distributed NGD network with reduced SA is presented in [11]. However, it is difficult to further reduce SA due to practical realization problem of characteristic impedance higher than 140 Ω in microstrip line technology.

In this paper, very low SA NGD networks with multiple-poles in GD characteristics are presented. The proposed circuits are based on shunt resistor that connected on short-circuited coupled lines with open circuited isolation port. The improvement of SA can be obtained due to high characteristic impedance and weak coupling coefficient of coupled line. The improved SA will help to reduce the gain burden of amplifier as well as out-of-band noise and can provide a stable operation when it is integrated with the RF system.

II. Design and Implementation

Fig. 1 show the structures of proposed NGD networks which consists of shunt resistors connected to short-circuited coupled lines with open circuited isolation port. In order to find electrical characteristics of proposed network, it is necessary to find the S-parameter and GD expressions for 1-pole structure of proposed NGD networks shown in Fig. 1(a).

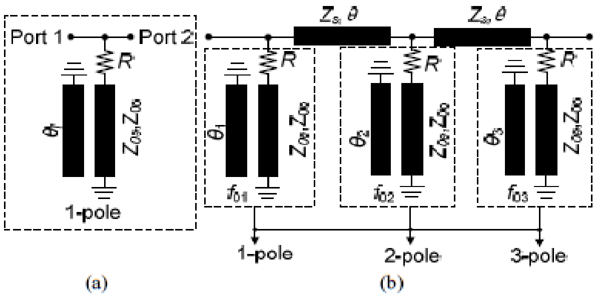

Fig. 1. Proposed structure of negative group delay circuits: (a) 1-pole and (b) multiple-poles.

To find the S-parameters of 1-pole NGD network, the ABCD-matrix of this circuit is given as

$$[A] = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{in}} & 1 \end{bmatrix}. \tag{1}$$

Where the value of Z_{in} is given as

$$Z_{in} = \frac{R_s\left(\cot^2\theta_i - Z_c C_{eff}^2 \csc^2\theta_i\right) + jC_{eff} Z_c \cot\theta_i}{\left(\cot^2\theta_i - Z_c C_{eff}^2 \csc^2\theta_i\right)}. \tag{2}$$

The characteristic impedance of coupled line Z_c and coupling coefficient C_{eff} [12] are given as

$$Z_c = \frac{2Z_{0e}Z_{0o}}{Z_{0e} - Z_{0o}} = Z_{0e}\frac{1 - C_{eff}}{C_{eff}} = Z_{0o}\frac{1 + C_{eff}}{C_{eff}}, \tag{3a}$$

$$C_{eff} = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}, \tag{3b}$$

where Z_{0e} and Z_{0o} are even- and odd-mode impedances of coupled lines. Expressing the frequency dependent electrical length $\theta_i = \pi f / 2f_{0i}$, the S-parameters of 1-pole NGD network are given as

$$S_{11} = S_{22} = \frac{-X_1 Z_0 / 2R_s}{X_3 + jX_4}, \tag{4a}$$

$$S_{21} = S_{12} = \sqrt{\frac{X_1^2 + X_2^2}{X_3^2 + X_4^2}} \angle \tan^{-1}\frac{X_2}{X_1} - \tan^{-1}\frac{X_4}{X_3}, \tag{4b}$$

where

$$X_1 = 2R_s\left(\cot^2\frac{\pi f}{2f_{0i}} - C_{eff}^2 \csc^2\frac{\pi f}{2f_{0i}}\right), \tag{5a}$$

$$X_2 = X_4 = 2C_{eff}^2 Z_c \cot\frac{\pi f}{2f_{0i}}, \tag{5b}$$

$$X_3 = \left(\cot^2\frac{\pi f}{2f_{0i}} - C_{eff}^2 \csc^2\frac{\pi f}{2f_{0i}}\right)(2R_s + Z_0). \tag{5c}$$

And Z_0, f and f_{0i} are termination port impedance, operating and design center frequencies, respectively. Therefore, the differential-phase GD of proposed structure can be obtained as

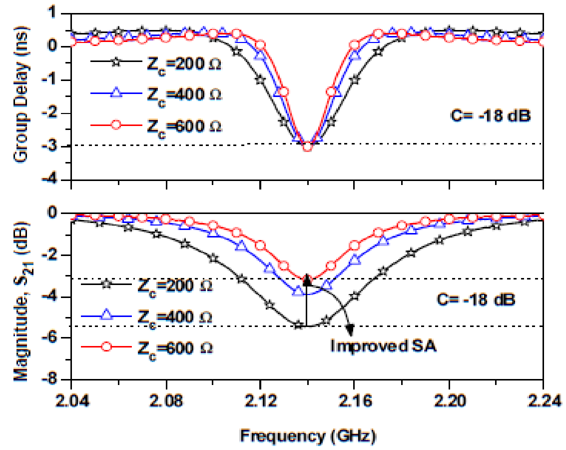

Fig. 2. Calculated group delay and signal attenuation of 1-pole NGD network with different values of Z_c.

$$\tau = -\frac{d\angle S_{21}}{d\omega} = \frac{X_2 X_1' - X_1 X_2'}{X_1^2 + X_2^2} + \frac{X_4 X_3' - X_3 X_4'}{X_3^2 + X_4^2}, \tag{6}$$

where

$$X_1' = \frac{R_s}{f_{0i}}\left(C_{eff}^2 - 1\right)\cot\frac{\pi f}{2f_{0i}}\csc^2\frac{\pi f}{2f_{0i}}, \tag{7a}$$

$$X_2' = X_4' = -\frac{1}{2f_{0i}} C_{eff} Z_c \csc^2\frac{\pi f}{2f_{0i}}, \tag{7b}$$

$$X_3' = \frac{1}{2f_{0i}}(2R_s + Z_0)\left(C_{eff} - 1\right)\cot\frac{\pi f}{2f_{0i}}\csc^2\frac{\pi f}{2f_{0i}}. \tag{7c}$$

Therefore, the maximum SA and GD at f_{0i} are obtained as (8) and (9).

$$\left|S_{21}\right|_{f=f_0} = \frac{2R_s}{2R_s + Z_0} \tag{8}$$

$$\tau\big|_{f=f_0} = -\frac{Z_0 Z_c}{4f_0 R_s C_{eff}\left(2R_s + Z_0\right)} \tag{9}$$

As seen from (8), the maximum SA at f_0 depends on R_s only. Similarly, the GD time is a function of R_s, Z_c, and C_{eff}. For better understating of (8) and (9), the calculated GD and SA for different Z_c and C_{eff} are shown in Fig. 2 and 3. In this case, the maximum achievable GD is maintained as -3 ns.

Fig. 2 shows the calculated of GD and SA for different Z_c with fixed C_{eff}=-18 dB. As seen from this figure, the SA is reduced as Z_c increases. However, the bandwidth of GD is narrowed. Therefore, there is a trade-off between NGD bandwidth and SA.

Fig. 3 shows the calculated GD and SA for different C_{eff}. In this case, the Z_c is assumed as 600 **Ω**. As seen from this figure, the SA is improved as C_{eff} decreases. However, the NGD bandwidth is slightly decreased. Therefore, there is also trade-off between C_{eff}, SA and NGD bandwidth.

As seen from the previous results, the 1-pole NGD bandwidth is small which prevents to use this circuit in practical applications. Therefore, it is necessary to enhance the NGD bandwidth.

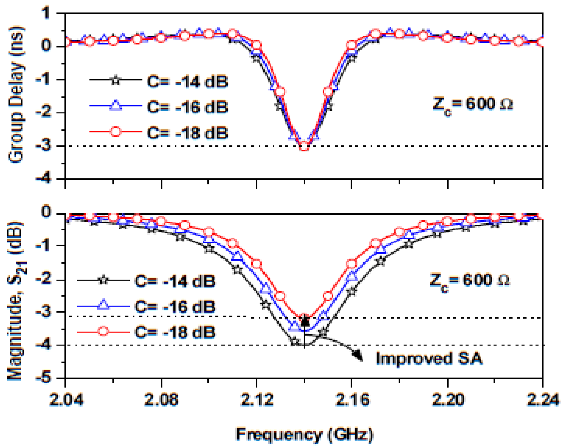

Fig. 3. Calculated group delay and signal attenuation of 1-pole NGD network with different values of C_{eff}.

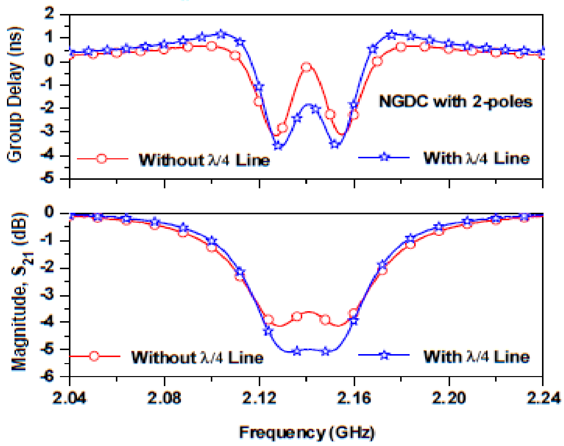

Fig. 4. Calculated group delay and signal attenuation of 2-poles NGD network.

Fig. 1(b) shows the proposed structure of NGD for the enhanced GD bandwidth with multi-poles characteristics. This structure consists of several 1-pole NGD circuits with slight different frequencies, which are connected with λ/4 TLs with characteristic impedance Z_s=50 Ω. Due to different resonant frequencies of resonators, the multiple poles in GD characteristics can be obtained.

Fig. 4 shows the simulated results of proposed 2-poles NGD network. In this case, 2-resonators with slightly different center frequencies f_{01}=2.125 GHz and f_{02}=2.155 GHz are used. The even- and odd-mode impedances of coupled line resonators are chosen as 90 Ω and 70 Ω. As seen from these figures, the NGD bandwidth is enhanced due to 2-poles characteristics. The comparison between with and without λ/4 TL is also presented. Resonators connected without λ/4 TL have higher peak in GD characteristics than those with λ/4 TL. Similarly, Fig. 5 shows the simulated GD and SA characteristics of 3-poles NGD network and compared with directly connected 3-poles NGD network (without λ/4 TL).

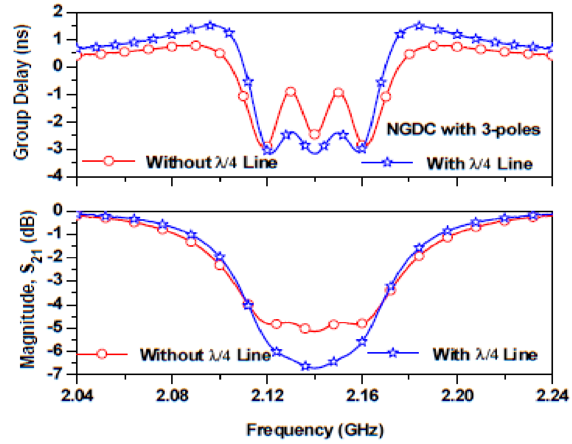

Fig. 5. Calculated group delay and signal attenuation of 3-poles NGD network.

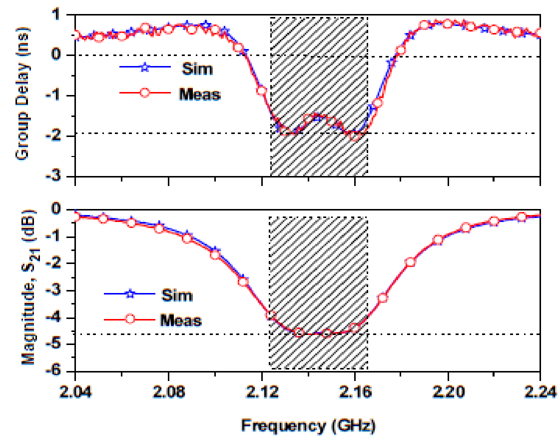

Fig. 6. Simulation and measurement result of 2-poles NGD network.

As seen from these figures, the proposed 3-poles NGD network with λ/4 TL provides good flatness characteristics than directly connected 3-poles NGD network.

III. Experimental Results

For experimental validation of proposed structure, the goal was to design GD network of -2 ns at center frequency of 2.14 GHz. For this purpose, the 2-poles and 3-poles NGD networks are designed and fabricated. The characteristic impedance of coupled line resonator is chosen as 630 Ω with C_{eff}=-18.06 dB. The R_s and Z_s are determined as 50 Ω. The circuit was fabricated using substrate RT/Duroid 5880 of Rogers with dielectric constant (ε_r) of 2.2 and thickness (h) of 31 mils.

Fig. 6 shows the simulation and measurement results of 2-poles NGD network. Center frequencies of resonators are fixed as f_{01}=2.132 GHz and f_{02}=2.16 GHz. The measurement results show good agreement with the simulations. From the measurement, the GD time is determined as -1.68±0.2 ns over the bandwidth of 42 MHz. The maximum SA at f_0=2.146 GHz is 4.58 dB, which is very small in comparison with the conventional NGD networks [4]-[9].

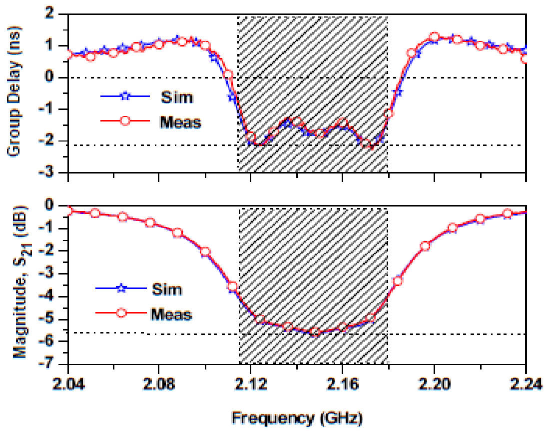

Fig. 7. Simulation and measurement result of 3-poles NGD network.

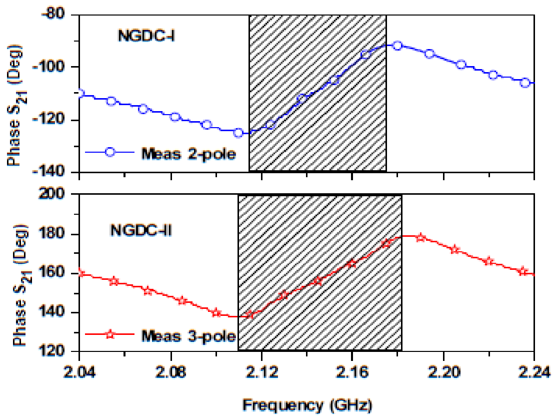

Fig. 8. Measured phase characteristics of S_{21} for 2-poles and 3-poles NGD network.

Fig. 7 shows the simulation and measurement results of 3-poles NGD network. Center frequencies of three resonators are fixed as f_{01} =2.126 GHz, f_{02}=2.149 GHz, and f_{03}=2.17 GHz, respectively. The measurement results show good agreement with the simulations. The measured GD time is -1.81±0.34 ns over the bandwidth of 64 MHz. The maximum SA at f_0=2.148 GHz is determined as 5.567 dB.

The measured phase characteristics of 2-poles and 3-poles NGD networks are shown in Fig. 8. As seen from these figures, the phase slope of S_{21} is positive over the certain frequency range which signifies the presence of NGD characteristics. The photograph of fabricated circuits is shown in Fig. 9.

IV. Conclusion

This paper demonstrated the design of negative group delay networks with highly improved signal attenuation with multi-poles group delay characteristics. The proposed structure is based on shunt resistors connected to short-circuited coupled line with open-circuit isolation port. The improved signal

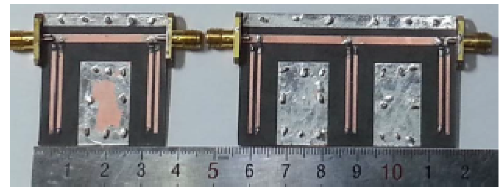

Fig. 9. Photograph of fabricated 2-poles and 3-poles NGD networks.

attenuation is obtained due to high characteristic impedance of coupled line and weak coupling coefficient. The proposed network can reduce the gain burden of gain amplifier and can provide the stable operation when integrated into RF system.

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