Distributed Transmission Line Negative Group Delay Circuit With Improved Signal Attenuation

Girdhari Chaudhary, *Member, IEEE*, and Yongchae Jeong, *Senior Member, IEEE*

***Abstract*—In this letter, a novel design and implementation of a distributed negative group delay circuit (NGDC) with reduced signal attenuation is demonstrated. By inserting an additional transmission line Z_2 into the conventional NGDC, the proposed NGDC provides further design parameters in order to obtain the required differential-phase group delay (GD) time and help to reduce the signal attenuation. As a result, the number of gain compensating amplifiers can be reduced, which can contribute to the efficiency enhancement as well as the stable operation when integrated into the RF system. Both theory and experiment are provided to validate the proposed structure. From the experiment, for the same GD time of −7.9 ns, the signal attenuation of the proposed circuit is 16.5 dB, an improvement signal attenuation of the conventional circuit of 19.2 dB.**

***Index Terms*—Distributed transmission line, low signal attenuation, negative group delay.**

I. Introduction

WITH a finite frequency interval of signal attenuation where the negative group delay (NGD) phenomenon is observed, higher frequency components of applied waveform are propagated with phase advancement without delay, relative to the lower frequency components [1]–[4]. These media have been used in many communication systems applications such as the shortening or reducing of delay lines [6], the efficiency enhancement of a feedforward linearization amplifier [7], frequency bandwidth enhancement in a feedback linearization amplifier [8], beam-squint minimization in phased array antenna systems [9], and eliminating phase variation with frequency in phase shifters [10].

Various approaches have been taken to the design of microwave active/passive NGDCs [2]–[10]. However, the passive NGDCs presented in previous works exhibited excess signal attenuation (up to 35 dB for −8 ns GD) which can cause serious stability issues when NGDC is integrated with systems such as the power amplifier linearization system. Therefore, for the same differential-phase GD, the passband signal attenuation is expected to be as small as possible. In [5], a composite NGDC with lower signal attenuation was presented. However, this circuit requires parallel lumped elements (such as an inductor, capacitor, and resistor) between two transmission lines.

Manuscript received June 19, 2013; revised August 22, 2013 and September 11, 2013; accepted September 12, 2013. Date of publication October 31, 2013; date of current version January 06, 2014. This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science, and Technology (2013006660).

The authors are with the Division of Electronic and Information Engineering, IT Convergence Research Center, Chonbuk National University, Jeonju, Chollabuk-do, Korea (e-mail: ycjeong@jbnu.ac.kr).

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Digital Object Identifier 10.1109/LMWC.2013.2287246

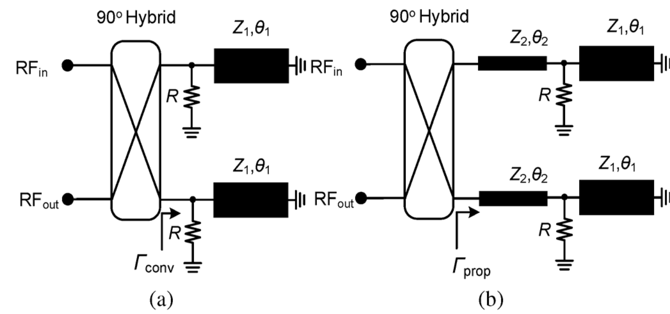

Fig. 1. Structure of distributed transmission line NGDC: (a) conventional [7] and (b) proposed structure.

In this letter, the design of a distributed transmission line NGDC with improved passband signal attenuation is presented that helps to reduce the gain burden of the amplifier as well as out-of-band noise and can provide a stable operation when it is integrated with the RF system.

II. Mathematical Analysis

Fig. 1 shows the structure of a conventional [7] and the proposed NGDC, which consists of a 3 dB hybrid coupler, resistor R, transmission lines with characteristic impedances of Z_1, and Z_2, and electrical lengths of θ_1, and θ_2, respectively. The S-parameter of the proposed 2-port NGDC is obtained by applying the port reduction method [3] as follows:

$$S=\begin{bmatrix}0 & -j\Gamma_{\rm prop}\\ -j\Gamma_{\rm prop} & 0\end{bmatrix}. \tag{1}$$

The input voltage reflection coefficient of the proposed NGDC is given as (2) assuming electrical length $\theta_1=\theta_2=0$

$$\Gamma_{\rm prop}=\frac{Z_2R+Z_2^2R-Z_0Z_1Z_2+j\left(Z_1Z_2^2-Z_0Z_1R\right)\tan\theta+Z_0Z_2Rcot\theta}{Z_1Z_2R+Z_2^2R+Z_0Z_1Z_2+j\left(Z_1Z_2^2+Z_0Z_1R\right)\tan\theta-Z_0Z_2Rcot\theta}. \tag{2}$$

Therefore, the differential-phase GD and transmission coefficient magnitude of the proposed circuit are obtained as (3) and (4), assuming $\theta=90^\circ$ at f_0

$$\tau|_{f=f_0}=-\frac{d\angle S_{21}}{d\omega}\bigg|_{f=f_0}=-\frac{Z_0Z_2(Z_1R^2+Z_2R^2-Z_1Z_2^2)}{2f_0Z_1\left(Z_2^4-Z_0^2R^2\right)} \tag{3}$$

$$|S_{21}|_{f=f_0}=\frac{Z_2^2-Z_0R}{Z_2^2+Z_0R} \tag{4}$$

where Z_0 is the termination port impedance. From (3), it is clear that the differential-phase GD depends on Z_2, Z_1, and R. Moreover, as seen from (4), the signal attenuation of the proposed

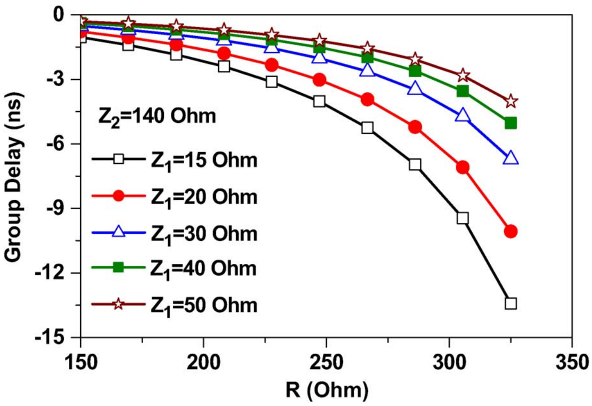

Fig. 2. Calculated NGD of the proposed NGDC according to R for different Z_1 at $f_0 = 2.14$ GHz.

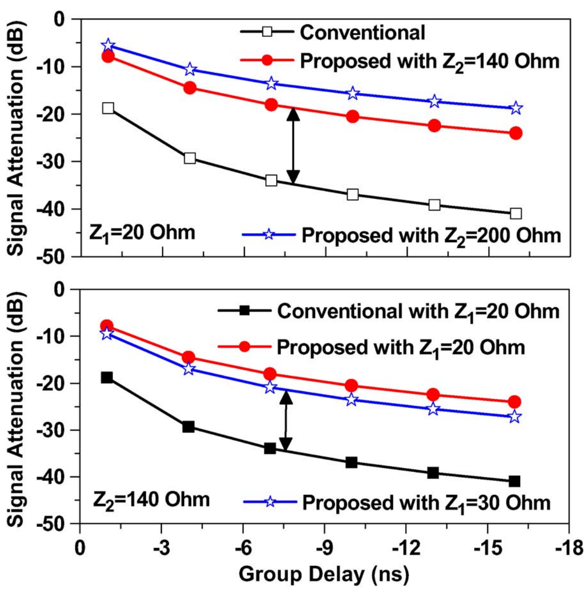

Fig. 3. Calculated signal attenuation according NGD at $f_0 = 2.14$ GHz.

circuit fully depends on Z_2 and R. To obtain low signal attenuation, Z_2 should be a high value, whereas R should be a low value. For good understanding and design, (3) and (4) can be plotted according to R for the different values of Z_1 and Z_2.

Fig. 2 demonstrates the NGD variation according to R for the different values of Z_1 with $Z_2 = 140\ \Omega$. As seen from this figure, R should be high when Z_1 varies towards the high value for the same amount of NGD. Therefore, a low value of Z_1 is preferable to obtain a high amount of NGD with a smaller value of R.

Fig. 3 shows the calculated signal attenuation according to the NGD amount for the different values of Z_1 and Z_2. As seen from the figure, the signal attenuation is smaller when Z_2 is high and Z_1 is low for the same amount of NGD. Therefore, a high Z_2 and low Z_1 are preferable for the design of small signal attenuation NGDC for the required NGD. When the signal attenuation is compensated with the general purpose broadband gain amplifier, the out-of-band noise floor will increase. The higher noise floor may deteriorate the system performances when this NGDC is integrated into the RF system. Therefore, the lower signal attenuation of the proposed NGDC has considerable advantages in terms of the system performance and stability.

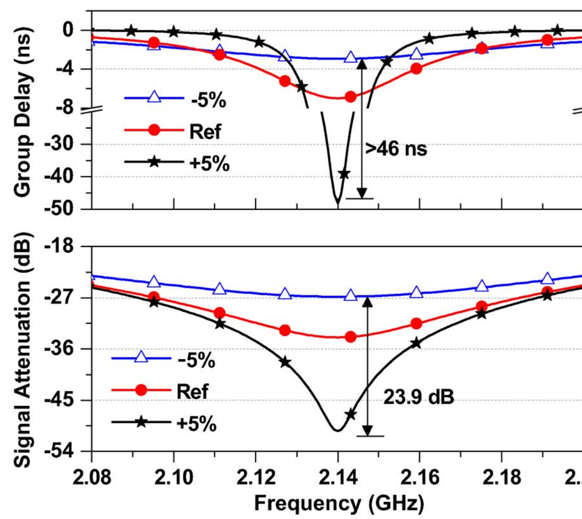

Fig. 4. Performance degradation of the conventional NGDC [7] with respect to ±5% resistance variation (Ref. refers to the value at room temperature).

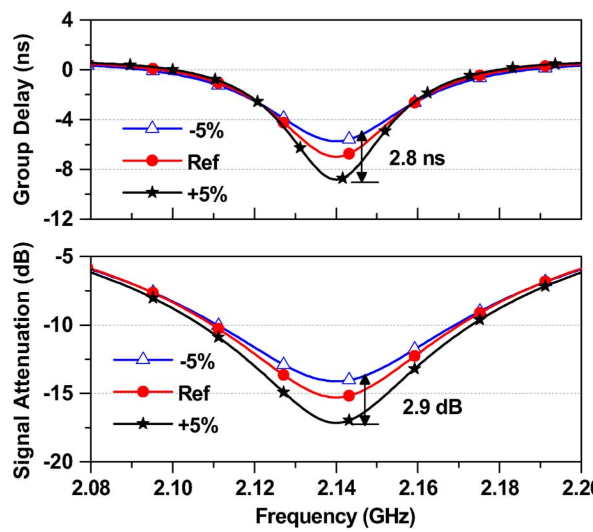

Fig. 5. Performance degradation of the proposed NGDC with respect to ±5% resistance variation (Ref. refers to the value at room temperature).

The temperature dependence of the resistor is represented as the following well-known relationship [5]:

$$\frac{\Delta R}{R_0} = \alpha \Delta T \tag{5}$$

where α, R_0, ΔR, and ΔT are the temperature coefficient, initial resistance, resistance variation, and temperature variation.

Fig. 4 shows the performance degradation of the conventional NGDC according to resistance variation due to temperature. As seen in this figure, the differential-phase GD and signal attenuation variation are greater than 46 ns and 23.9 dB, respectively, when the resistance variation of ±5% is assumed. This may seriously degrade the system performances, such as the overall signal cancellation performance of the power amplifier linearization technique.

Fig. 5 shows the performance degradation of the proposed NGDC assuming the same resistance variation of ±5%. The differential-phase GD and signal attenuation variation are only 2.8 ns and 2.9 dB, respectively, in the case of the proposed

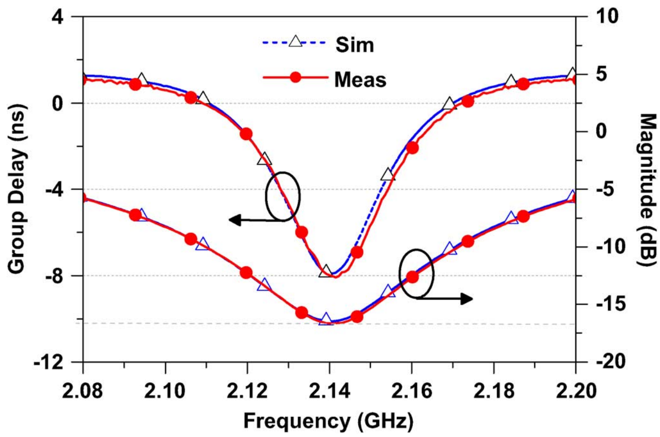

Fig. 6. Simulation and measurement results of low signal attenuation NGDC.

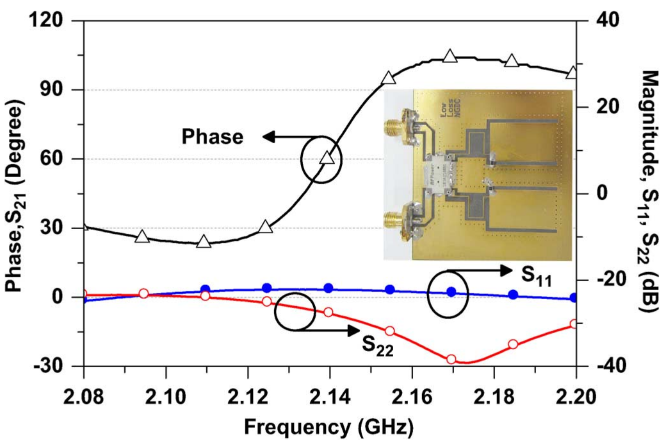

Fig. 7. Measured input and output return losses and phase response.

TABLE I
PERFORMANCE COMPARISON

	Center Frequency (GHz)	Circuit Type	Group Delay (ns)	Signal Attenuation (dB)	For R±5% variation	
					ΔGD (ns)	ΔSA (dB)
[3]-[4]	1.00	MMIC	-10	≥ 30	x	x
[5]*	2.14	Composite	-6.7	14.3	<2.2	<2.30
[7]-[8]	2.14	Distributed	- 6.0	33.2	>46	>23.9
This work	**2.14**	Distributed	**-7.9**	**16.5**	**<2.8**	**<2.90**

ΔGD = change in group delay from reference value
ΔSA = change in signal attenuation from reference value
* = consists of parallel lumped elements (R, L, C) in between two transmission lines

NGDC. This confirmed that the proposed NGDC is considerably less temperature dependent than the conventional NGDC.

III. SIMULATION AND MEASUREMENT RESULTS

To validate the proposed NGDC experimentally, the microstrip NGDC is designed for the GD -8 ns at the operating center frequency (f_0) of 2.14 GHz and is fabricated on the substrate with a dielectric constant (ε_r) of 2.2 and thickness (h) of 31 mils. For the 3 dB hybrid coupler, a quadrature surface mount hybrid coupler from Anaren S03A2150N1 is used. The values of Z_1, Z_2, and R used in the experiment are given as 20, 140, and 330 Ω, respectively.

Fig. 6 shows the simulation and measurement result of the proposed NGDC. As seen in the figure, the measurement results are in good agreement with the simulation results. The measured GD and signal attenuation at 2.14 GHz are -7.9 ns and 16.5 dB..

Fig. 7 shows the measured input, output return losses and the phase response over the bandwidth of 120 MHz. As seen in this figure, the slope of phase is positive over a certain region. This positive slope parameter can be used to cancel out the negative phase slope to obtain a zero group delay or phase compensation response over a wide bandwidth. The performance comparison of the proposed circuit is shown in Table I. As seen in the table, the proposed circuit has improved signal attenuation and less performance degradation due to R variation. Even though the performance of the composite NGDC [5] is slightly better than that of the proposed work, it is difficult to implement at microwave frequencies due to the use of lumped elements parallel to the RLC circuit between the two transmission lines. Therefore, the simple circuit design and implementation of the proposed NGDC is one of the advantages over composite NGDC [5] because of the fully distributed transmission lines. Fig. 7 shows a photograph of the fabricated NGDC.

IV. CONCLUSION

In this letter, a distributed transmission line negative group delay circuit with improved signal attenuation is proposed. The optimum design method is explained based on the derived general design equations. The improved signal attenuation of the proposed circuits can reduce the gain burden of the amplifier block, which can help to contribute to the efficiency enhancement as well as to the out-of-band noise reduction and stable operation when it is integrated with another RF system. The proposed circuit is less sensitive to resistance variation due to temperature than the conventional circuit.

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