# A Design of Composite Negative Group Delay Circuit with Lower Signal Attenuation for Performance Improvement of Power Amplifier Linearization Techniques

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***Abstract* — In this paper, we propose a novel composite negative group delay circuit to reduce the signal attenuation required to obtain negative group delay. It is already known that negative group delay can be obtained in a specific frequency of signal attenuation. For the same negative group delay of -6 ns, the signal attenuation of the conventional circuit is 31.25 dB, while the proposed composite circuit involves signal attenuation of only 13.9 dB. As a result, the number of gain compensating amplifiers can be reduced. This contributes to the efficiency enhancement as well as out-of-band noise reduction and stable operation when integrated into the power amplifier linearization system.**

***Index Terms* — Attenuation, efficiency enhancement, negative group delay, propagation losses.**

## I. Introduction

Recently, some interesting studies of the negative group delay concept have led to its experimental validation through the realization of its electronic circuit. In a specific and narrow frequency band of signal attenuation, absorption, or in an anomalous dispersion, the group velocity is observed to be greater than that of *c*, the speed of light in a vacuum, or even to be negative. Faster-than-*c* phenomenon was defined as the superluminal group velocity, and negative group velocity is also referred to as negative group delay. The experimental validations of the theoretical analysis about those phenomena have been presented in the previous studies as a part of Physics and radio frequency (RF) electronic circuit approaches [1]-[13]. A research on the efficiency enhancement of an analog feed-forward power amplifier was proposed for commercial WCDMA base-station application by using the distributed element NGDC [9]. NGDC was also successfully applied to an analog RF feedback amplifier to increase the distortion cancellation bandwidth [10].

Due to the band-stop transmission characteristic of the NGDC, out-of-band noise floor is always higher than pass-band. In case of achieving practical amount of negative group delay, the out-of-band noise floor to pass-band ratio amounts up to 35 dB. This phenomenon may cause serious stability issues when the NGDC is integrated into a system with loops, especially in a feed-back topology. For the same negative group delay, therefore, the pass-band signal attenuation is expected to be as small as possible in terms of gain compensation and stable operation.

This paper presents a novel composite negative group delay circuit, which consists of distributed element and lumped element, to obtain negative group delay with low signal attenuation condition. The major benefits that can be achieved with the proposed topology are efficiency enhancement accomplished by reducing the number of gain compensating small signal amplifier, and out-of-band noise reduction. Performance degradation due to temperature variation can also be improved, which will be further analyzed in this paper.

## II. Mathematical Analysis

Fig. 1 shows the schematic diagram of the proposed composite NGDC. The proposed circuit consists of a 3 dB branch line coupler, parallel resistor $R_2$, micro-strip transmission line element with electrical length $\theta$, where $\theta=\theta_1+\theta_2$, and characteristic impedance $Z_1$ and $Z_2$, and lumped element resonance circuit ($R_1LC$) inserted in between the transmission line elements. To understand the operation, we analyzed the circuit by finding the general design equation of the NGD branch of the circuit ($Z_{IN}$). For simple analysis and symmetric design, we assumed that $Z_1=Z_2=Z_0$, where $Z_0$ is a termination impedance of the branch line coupler, and $\theta_1=\theta_2=45°$. Group delay $\tau$ and the reflection coefficient $\Gamma_{in}$ at the resonance frequency ($\omega_0$) can be derived as follows:

$$\tau(\omega_0)=\frac{1}{1+[R_1R_2/\alpha]^2}\left[\frac{\beta R_1^2(R_2+Z_0)-2R_1R_2}{\omega_0\alpha}-\left(\frac{-2\alpha+\beta R_2}{\omega_0\alpha^2}\right)R_1R_2\right]-\frac{1}{1+[R_1R_2/\gamma]^2}\left[\frac{\beta R_1^2(R_2-Z_0)+2R_1R_2}{\omega_0\gamma}+\left(\frac{-2\gamma-\beta R_2}{\omega_0\gamma^2}\right)R_1R_2\right] \quad (1)$$

$$\Gamma_{in}(\omega_0)=\frac{\alpha^2+(R_1R_2)^2}{\gamma^2+(R_1R_2)^2}, \quad (2)$$

where $\alpha=R_1R_2-Z_0(R_1+2R_2)$, $\beta=2\omega_0CR_1^2$, $\gamma=R_1R_2+Z_0(R_1+2R_2)$, and $\omega_0=1/\sqrt{LC}$.

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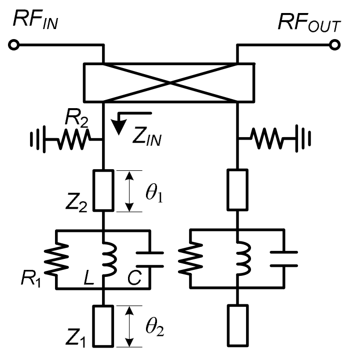


Fig. 1. Schematic diagram of the proposed composite negative group delay circuit (NGDC).

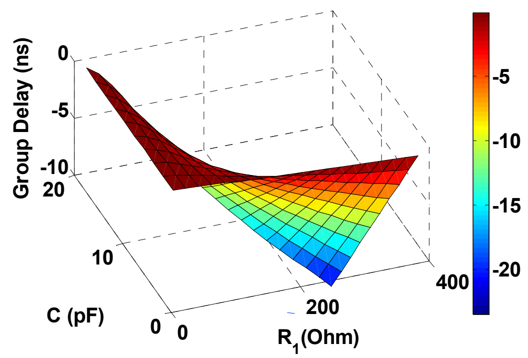


Fig. 2. Calculated group delay according to various $R_1$ and $C$ ($\omega_0$= $2\pi$ ×2.14 GHz, $Z_0$=$R_2$=50 Ω, and the color bar shows the amount of group delay).

The calculated group delay in (1) and reflection coefficient in (2) at the resonance frequency using MATLAB (in dB scale) are illustrated in Fig. 2 and Fig. 3, respectively. From Fig. 2, it is verified that the group delay between -20 to 0 ns can be obtained according to the various combinations of $R_1$ and $C$ at the resonance frequency. Now that the equation is derived from the 1-port circuit, the reflection coefficient equals to the insertion loss of the circuit when expressed in dB scale.

From Fig. 3, the insertion loss of the proposed composite NGDC is estimated to be around 15 dB. It is well known that a resistor is temperature-sensitive component. The value of $R_1$ under 100 Ω is not preferable because the insertion loss is very sensitive to the resistance variation. Among various $R_2$ values, we can obtain $R_1$-independent constant insertion loss characteristic with $R_2$=50 Ω. In our design, $R_1$=280 Ω and $R_2$=50 Ω are chosen for temperature-independent design.

## III. Circuit Simulation

We simulated the circuit schematic of Fig. 1 by using ADS 2009U1 of Agilent Technologies to show the validity of the proposed circuit.

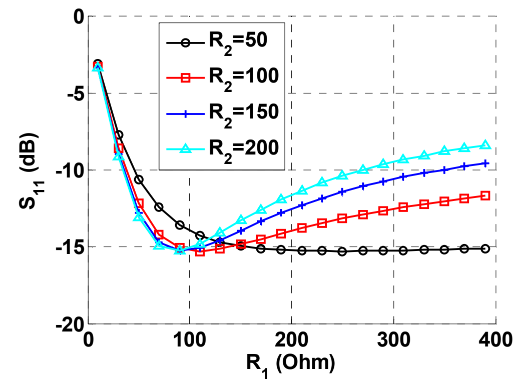


Fig. 3. Calculated reflection coefficient according to $R_1$ and $R_2$.

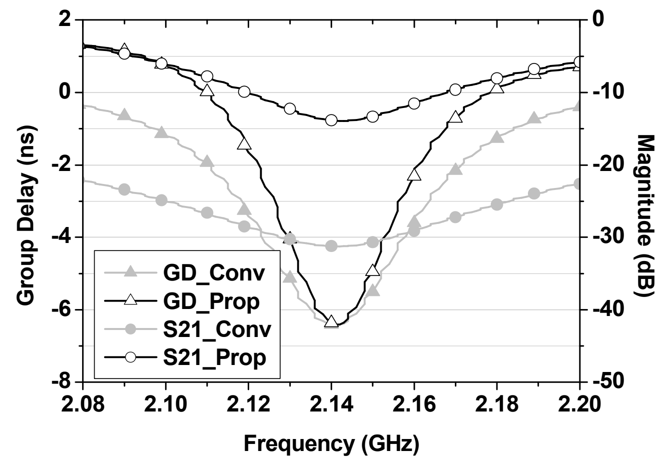


Fig. 4. Comparison of the simulation results between the conventional and the proposed NGDC ($C$=17.75 pF, $L$=0.3 nH, $R_1$=280 Ω, $R_2$=50 Ω, $\theta_1$= $\theta_2$=45°, $Z_1$=$Z_2$=$Z_0$=50 Ω).

### *A. Out-of-band noise floor to pass-band ratio*

Fig. 4 shows the simulated insertion loss and group delay of the conventional and composite NGDC. In case of achieving the same group delay of -6.5 ns, the signal attenuation of the conventional circuit at the resonance frequency is 31.25 dB, while the proposed composite circuit involves the signal attenuation of only 13.9 dB. If we compensate this attenuation up to 0 dB with the general purpose broadband gain amplifier, out-of-band noise floor will also rise. Higher noise floor may become a source of oscillation when the circuit is integrated into a system, especially in a feed-back linearization. Therefore the lower signal attenuation of the proposed composite NGDC has a great advantage in terms of stability.

### *B. Temperature dependence analysis*

Temperature dependence of a resistor is represented with the following well-known relationship:

$$\frac{\Delta R}{R_0} = \alpha \Delta T, \qquad (3)$$

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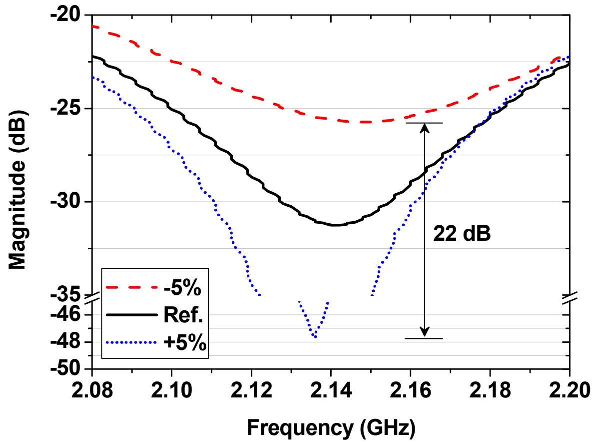
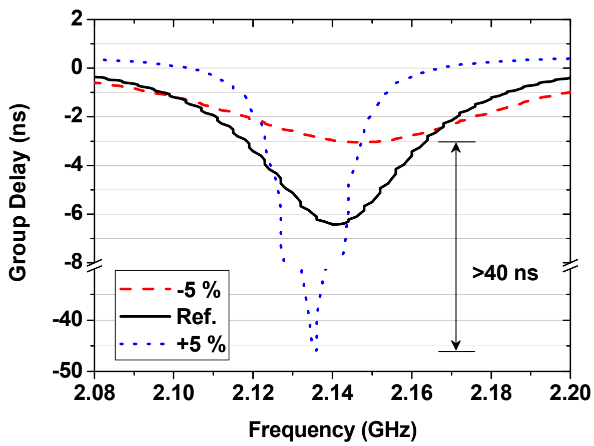



(a)



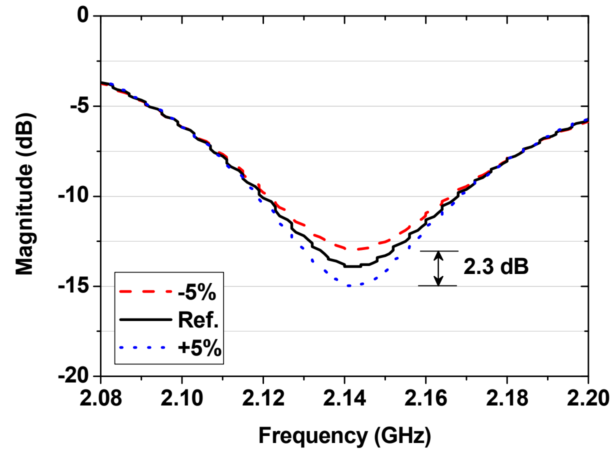

(b)

Fig. 5. Performance degradation of the conventional NGDC with respect to ±5 % resistance variation (Ref. means the value at room temperature): (a) insertion loss and (b) group delay.

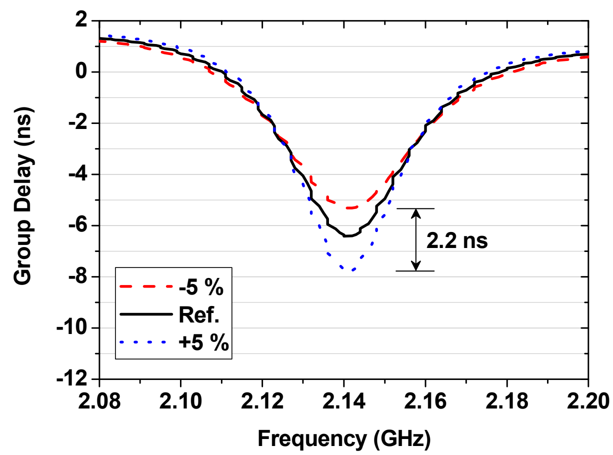
where   is a temperature coefficient of resistance, $R_0$ is initial resistance, $\Delta R$ is resistance variation, and $\Delta T$ is temperature change. For the analysis, we assumed the resistance variation of ±5 %. For worst case analysis, only peak-to-peak variation is considered, excluding the case when the positive and negative variation cancels out each other.

Fig. 5 shows the performance degradation of the conventional NGDC. The insertion loss of the conventional circuit depends only on the parallel resistor $R_{RP}$. The insertion loss and group delay variation amounts to 22 dB and over 40 ns, respectively. This may seriously degrade the overall signal cancellation performance of the power amplifier linearization technique.

Fig. 6 shows the performance degradation of the composite NGDC. As discussed in Section II, the insertion loss and group delay of the composite NGDC depends on both $R_1$ and $R_2$. The insertion loss and group delay variation amounts only to 2.3 dB and 2.2 ns, respectively, as shown in Fig. 6. If we consider the case when the positive and negative variation




(a)




(b)

Fig. 6. Performance degradation of the proposed composite NGDC with respect to ±5 % resistance variation (Ref. means the value at room temperature): (a) insertion loss and (b) group delay.

cancels out each other, the temperature dependence will be far less in the proposed circuit.

## IV. Experiments

For experimental verification, the proposed composite NGDC was fabricated at the resonance frequency of 2.14 GHz with the component values given in the earlier discussion. Estimated group delay and insertion loss from the circuit simulation were -6.5 ns and 15 dB, respectively.

Fig. 7 shows the simulation and measurement results. Measured group delay and insertion loss at the resonance frequency were -6.7 ns and 14.3 dB, respectively. Generally, measured results agree well with the simulation over the bandwidth of 120 MHz. Minor but acceptable discrepancy between the traces may be due to the difference in the parasitic components which are considered in the simulation and experiment.

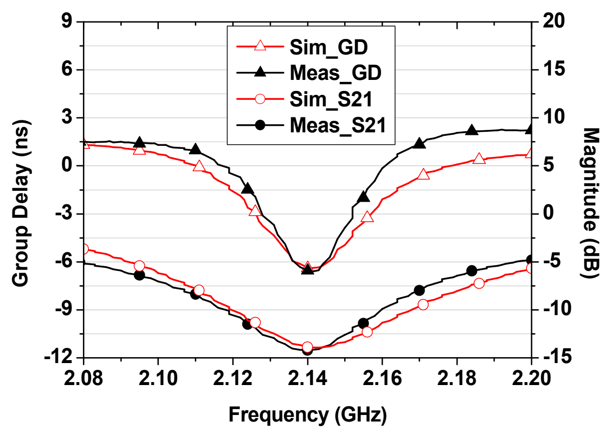



Fig. 7. Measured group delay and insertion loss (GD refers to group delay).

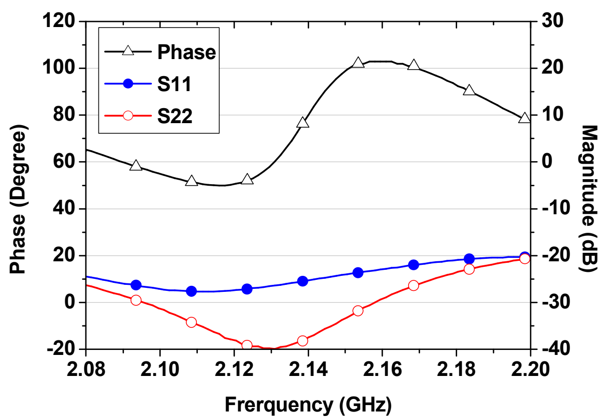



Fig. 8. Measured input and output return loss and phase response.

Fig. 8 shows the measured input and output return loss and the phase response. Over the bandwidth of 120 MHz, input and output return loss show good matching, which can be expected from the fact that the composite NGDC takes the reflection topology. Regarding the phase, there is a region with the positive slope over the frequency. This is another important physical property of negative group delay, and the positive slope can be used to cancel out the negative phase slope, which is a natural phenomenon in most cases, to obtain zero or negative group delay response. Reverse phase slope was observed over 40 MHz bandwidth for a single stage composite NGDC.

## V. Conclusion

In this paper, we proposed a novel composite negative group delay circuit to reduce the signal attenuation required to obtain negative group delay. Optimum design method is explained based on the derived general design equation. Reduced number of general purpose gain amplifier can contribute to the efficiency enhancement as well as out-of-band noise reduction and stable operation when integrated into the power amplifier linearization system. Also, we analyzed the temperature dependence of the proposed circuit and proved that the composite NGDC has far less temperature dependence than the conventional topology. We are now working to adapt this circuit into the RF power amplifier linearization technique.

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