Synthesis of Reflection Type Negative Group Delay Circuit Using Transmission Line Resonator

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Abstract— **Design equation and synthesis of reflection type negative group delay circuit (NGDC) using transmission line resonator (TLR) are presented. From the mathematical analysis, general equations are derived and validated with simulation for lumped element (LE) equivalent circuit. TLR-loaded reflection type NGDC is proposed to overcome the limited availability of component values required for LE structural NGDC. As a design example, single unit TLR-loaded NGDC with group delay (GD) of -8ns is designed. Simulation results agreed pretty well with the proposed design equation. To obtain broadband negative group delay with rigid flatness specification, 2-stage reflection type TLR-loaded NGDC with total group delay of -7 ns, -1.7dB loss, and 30 MHz bandwidth around 2 GHz, in which magnitude flatness of 0.1dB and group delay flatness of 0.5 ns is maintained, are fabricated and demonstrated.**

I. INTRODUCTION

Negative group delay (NGD) is quite an intriguing property and sometimes confusing concept that typical materials in our world do not usually have. NGD is open to dispute because it does not seem to follow special relativity and causality at the first glance, but those issues have been organized as many researchers reported various experimental results with proper explanations [1]. In a specific frequency band of anomalous dispersion, the group velocity is observed to be greater than c, the speed of light in a vacuum, or even be negative, and it is defined as the superluminal group velocity [2]. Researchers have been trying to find the application of NGD or the superluminal effect to the various types of electronic circuits [3]-[6].

Group delay usually is a critical property as well as magnitude and phase that should be matched to achieve broadband signal cancellation such as in a feedforward linear power amplifier (LPA) [7]. Delay element at the output of the main PA is one of sources in the extremely poor efficiency of a feedforward LPA. There have been some efforts to design NGD circuits for feedforward LPA application [8]. However, too narrow bandwidth (two-tone spacing of 2 MHz), poor input/output reflection coefficients, limited available components that is main limitation of the LE circuit, and the fact that there is no intuitive general design equation are not suitable for LPA system amplifying broadband modulated signals, wideband code division multiple access (WCDMA) signal of which bandwidth is roughly 5 MHz for 1 frequency allocation (FA) signal, for example. Considering the inter-modulation distortion (IMD) signal, bandwidth requirement would be much harder to satisfy.

To overcome the limitations of the previous NGD circuit design, we present general design equation and synthesis of reflection type NGDC using TLR. Next section deals with the derivation of design equation from the LE equivalent circuit, and covers the basic theory of conversion from LE to TLR. To improve the reflection coefficient, reflection type TLR-loaded NGDC with 90° hybrid is designed. Finally, 2-stage broadband reflection type TLR-loaded NGDC with 0.1dB magnitude flatness and 0.5ns group delay flatness for 30 MHz bandwidth was designed and fabricated.

II. SYNTHESIS OF REFLECTION TYPE NEGATIVE GROUP DELAY CIRCUIT

Negative group delay may mean time-advance or speed which is faster than the light in a vacuum, not time-delay as usual. By the way, let the people in physics consider the causality problem, and here in this work we will try to derive the design methodology and applications. NGD also means the sign of the equation representing group delay (GD), $GD = -(d\phi / d\omega)$, where ϕ is the phase response of a network and ω is the angular frequency, is negative. It implies we could obtain zero-transmission time when the conventional network is combined with the NGDC as a result of basic summing function. Zero-transmission time is a very attracting feature in the various microwave and RF circuit design.

Design equations for the transmission type series-parallel (SP) and shunt-series (SS) NGDC were already derived in [9], so we will not repeat the same contents here. Main difference between transmission type and reflection type is that the former can be directly used as a transmission element such as in a π-network, but the latter should be employed with 90° hybrid as a reflective circuit. While the former has an input/output reflection coefficient problem, the latter does have no matching problem in case of a broadband application.

A. Reflection Type Lumped Element NGDC

Fig. 1 shows the reflection type LE NGDC. Basically, it is a parallel RLC resonator. Input impedance of reflective parallel (RP) network can be represented as (1), and magnitude and phase component of input reflection coefficient Γ_{RP} can be derived as (2). Equations for GD can be obtained by partial differentiating (3) in respect to ω and substituting resonance condition. In (4), GD is a function of capacitance (C_{RP}) and resistance (R_{RP}). Also input reflection magnitude at the resonant frequency can be explained as (5).

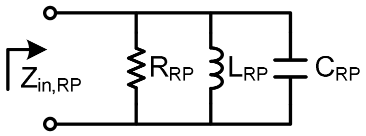


Fig. 1. The reflection type LE NGDC.

$$Y_{in,RP} = \frac{1}{R_{RP}} + j\left(\omega C_{RP} - \frac{1}{\omega L_{RP}}\right) \tag{1}$$

$$\Gamma_{in,RP} = \frac{Y_0 - Y_{in}}{Y_0 + Y_{in}} = \frac{\sqrt{[(R_{RP}Y_0 - 1)\omega L_{RP}]^2 + [(\omega^2 L_{RP}C_{RP} - 1)R_{RP}]^2}}{\sqrt{[(R_{RP}Y_0 + 1)\omega L_{RP}]^2 + [(\omega^2 L_{RP}C_{RP} - 1)R_{RP}]^2}} \angle \phi_{in,RP} \tag{2}$$

$$\phi_{in,RP} = -\tan^{-1}\left(\frac{(\omega^2 L_{RP}C_{RP} - 1)R_{RP}}{(R_{RP}Y_0 - 1)\omega L_{RP}}\right) - \tan^{-1}\left(\frac{(\omega^2 L_{RP}C_{RP} - 1)R_{RP}}{(R_{RP}Y_0 + 1)\omega L_{RP}}\right) \tag{3}$$

$$GD_{RP}\big|_{\omega=\omega_0} = -\frac{d\phi_{in,RP}}{d\omega}\bigg|_{\omega=\omega_0} = \frac{4R_{RP}^2 Y_0 C_{RP}}{(R_{RP}Y_0)^2 - 1} \tag{4}$$

$$\Gamma_{RP}\big|_{\omega=\omega_0} = \frac{1 - R_{RP}Y_0}{1 + R_{RP}Y_0} \tag{5}$$

For the intuitive understanding, (4) and (5) are represented in a graphical manner according to C_{RP} and R_{RP} as in Fig. 2 (a) and (b), respectively. The amount of NGD is proportional to R_{RP} and C_{RP}, provided that R_{RP} does not exceed 50 Ω. When R_{RP} >50 Ω, NGD cannot be achieved. From Fig. 2, it can be inferred that more NGD induces more signal attenuation, delivering trade-off to the designer, since the reflection coefficient is equal to insertion loss for the reflection type circuit. One major difficulty of the LE circuit is the availability of the component values. Therefore, we transformed LE circuit into distributed network using transmission resonator concept.

B. Synthesis of Reflection Type NGDC using Transmission Line Resonator

In many microwave circuit design, a specific length of open or short terminated transmission line is often used as a resonator [10]. Fig. 3 shows some examples of transmission line resonators. It is noted that Fig. 3 (a) has length of odd multiple of one-quarter wavelength, and Fig. 3 (b) has length of multiple of one-half wavelength, and usually n=1 is chosen for small size. RP network in Fig. 1 can be transformed either to quarter-wave short circuit (QS) or half-wave open circuit (HO). Characteristic impedance of each circuit can be derived as follows:

$$Z_{0,HO} = \frac{1}{(2\omega_0 C_{RP}/\pi)} \tag{6}$$

$$Z_{0,QS} = \frac{1}{(4\omega_0 C_{RP}/\pi)} \tag{7}$$

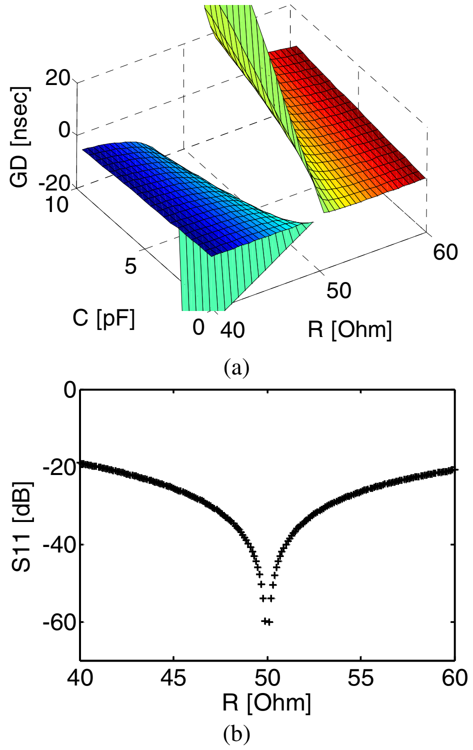


Fig. 2. Mathematical simulation results (a) group delay as a function of C_{RP} and R_{RP} and (b) reflection coefficient according to R_{RP}.

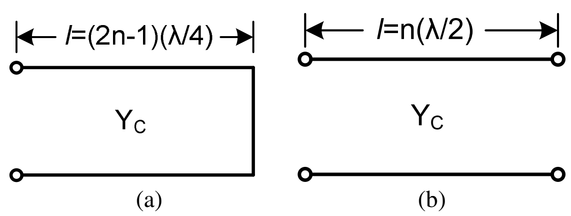
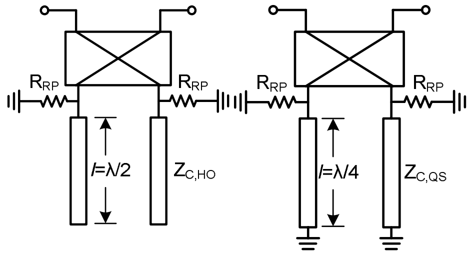


Fig. 3. Some transmission line resonators: (a) quarter-wave short circuit and (b) half-wave open circuit.

C. Reflection Type NGDC using 90° Hybrid Coupler

As previously explained, the reflective type NGDC should be used with 90° hybrid, as shown in Fig. 4, to obtain good reflection coefficient characteristic. Two kinds of circuit implementation is possible, HO TLR-loaded (a) and QS TLR-loaded (b) reflection type NGDC. To implement the circuit with minimum size, QS structure is preferred.



(a) (b)

Fig. 4. Reflection type NGDC using 90° hybrid and transmission line resonators: (a) HO TLR-loaded reflection type NGDC and (b) QS TLR-loaded reflection type NGDC.

III. Circuit Simulation and Experimental Verification

For experimental verification, we set our goal to design a 2-stage reflection type TLR-loaded NGDC with total group delay of -8 ns, 0 dB loss, and 30 MHz bandwidth centered on 2.14 GHz, in which magnitude flatness of 0.1dB and group delay flatness of 0.5 ns is maintained. To achieve our goal, we followed design step explained in the previous section.

Fig. 5 is the simulation schematic of LE reflective parallel NGDC and its TLR-loaded equivalent circuit. Using (4) and Fig. 2 (a), we obtained R_{RP}=47.2 , C_{RP}=1.107 pF, and L_{RP}=1.107 nH to obtain GD of -8 ns, and the estimated reflection loss was -31dB from (5) when the center frequency is 2.14 GHz. Then, LE values are transformed to distributed elements using (7), and the calculated characteristic impedance of the QS is 60.16 .

Fig. 6 is the simulation result using Agilent ADS2008a. As expected, results agree pretty well with mathematical calculation using the proposed synthesis method. Also, LE to TLR conversion has been performed without any problem.

Next step is to design 90° hybrid coupled reflective NGDC optimized for each upper and lower edge of target frequency band, 2.125 GHz and 2.155 GHz (2.14 ± 15 MHz), as shown in Fig. 7. Unit cells for each band have GD of -7 ns and insertion loss of -33dB. About 1.5 ns error is due to 90° hybrid and other connecting elements.

Final step is to connect those two units in a cascade manner. We can obtain flat response at the center of the band, although there would be about -60 dB insertion loss. This loss can be compensated by small signal high gain amplifier. Total circuit schematic is represented in Fig. 8. There is the compensation capacitor connected parallel to the R_{RP}. This is to compensate the parasitic inductance of a chip resistor. One gain amplifier consists of 2-stage ERA-5SM MMIC amplifier with total gain around 30 dB, and output power is not in consideration.

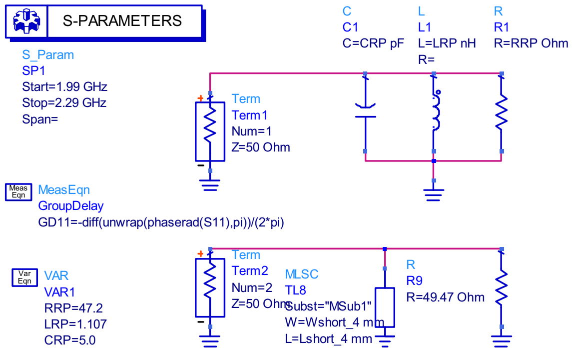


Fig. 5. Simulation schematic for LE reflective parallel NGDC and TLR-loaded NGDC.

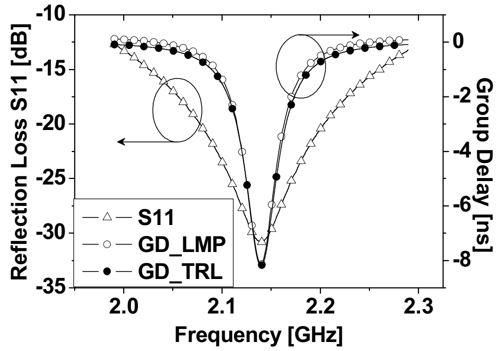
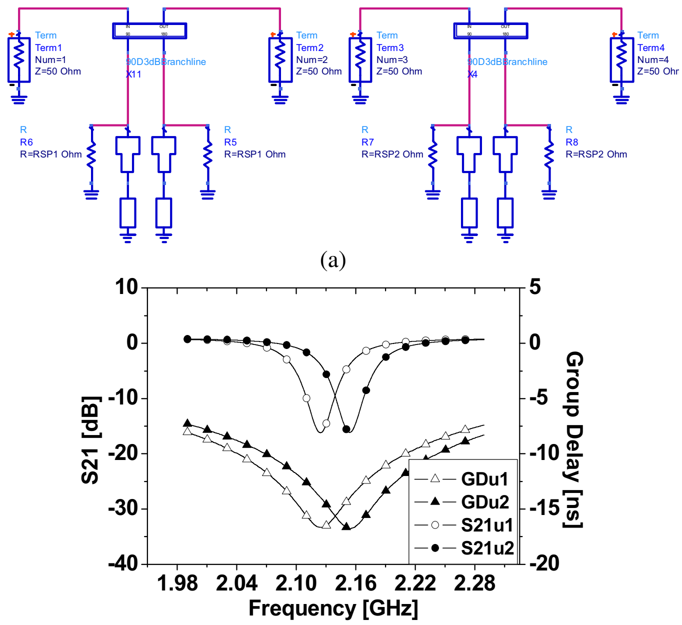


Fig. 6. Simulated reflection loss and group delay characteristics of single unit LE and TLR-loaded NGDC.



(a)

(b)

Fig. 7. Reflection type unit cells optimized for 2.125 GHz and 2.155 GHz: (a) simulation schematics and (b) simulated group delay and magnitude response.

Fig. 9 and Fig. 10 is the simulation and measurement result of the proposed 2-stage reflection type TLR-loaded NGDC.

Measured results show good agreement with simulation results, achieving GD of -7 ns, -1.7 dB loss. From marker readouts of a network analyzer, GDs are -7.29 ns, -7.11 ns, and -7.58 ns at 2.125 GHz, 2.14 GHz, and 2.155 GHz, respectively. Insertion losses at each frequency band are -1.74 dB, -1.76 dB, and -1.65 dB, respectively. As expected from the simulation, GD error of 1 ns is due to connecting elements and small signal amplifier. Fig. 11 shows the photograph of a 2-stage broadband reflection type TLR-loaded NGDC.

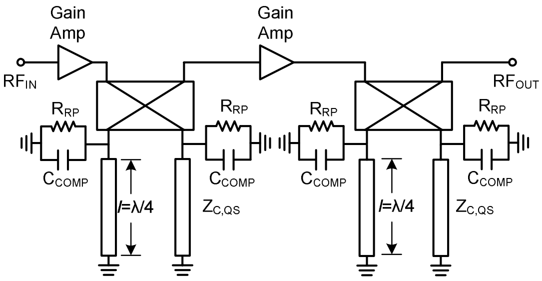


Fig. 8. Circuit diagram of 2-stage reflection type TLR-loaded NGDC.

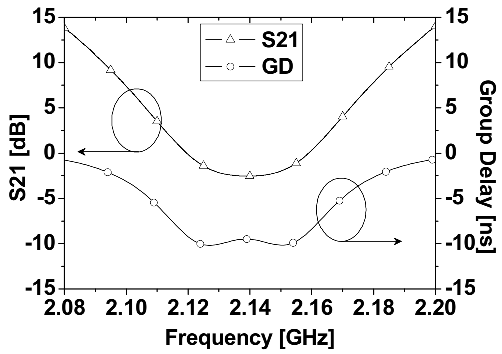


Fig. 9. Simulated magnitude and group delay response of reflection type TLR-loaded NGDC.

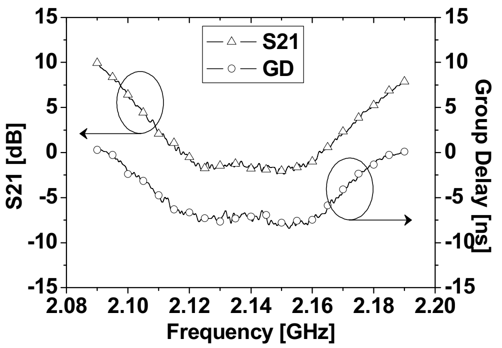


Fig. 10. Measured magnitude and group delay response of reflection type TLR-loaded NGDC.

IV. Conclusion

We have proposed design equation and synthesis of reflection type NGDC using TLR. From the mathematical analysis, general equations are derived and validated with simulation for LE equivalent circuit. Then, TLR-loaded reflection type NGDC is proposed to overcome the limited availability of component values required for LE structure. To obtain negative group delay with rigid flatness specification, 2-stage reflection type TLR-loaded NGDC with total group delay of -7 ns, -1.7dB loss, and 30 MHz bandwidth around 2 GHz, in which magnitude flatness of 0.1dB and group delay flatness of 0.5 ns is maintained, are fabricated and demonstrated. As a future work, the proposed circuit is being employed to the feedforward LPA amplifying broadband modulated signal.

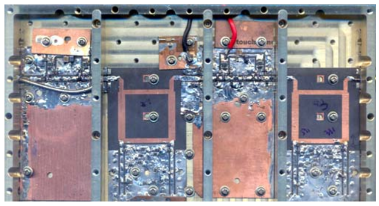


Fig. 11. Photograph of a 2-stage reflection type TLR-loaded NGDC.

Acknowledgment

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