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A Design of Size-Reduced Negative Group Delay Circuit Using a Stepped Impedance Resonator

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***Abstract* — A design method to reduce the size of the planar negative group delay circuit (NGDC) is proposed by using a stepped impedance resonator (SIR) concept. From the conventional transmission line resonator, an equivalent stepped impedance resonator with reduced size is derived. To validate the derivation, the reflection coefficient and group delay response are compared between the two types of one-port NGDC. Finally, the reflection topology NGDC using a stepped impedance resonator is fabricated and tested. Maintaining its intrinsic electric properties, total size of the circuit is reduced to 72% from its original size.**

***Index Terms* — Negative group delay, stepped impedance resonator, transmission line resonator.**

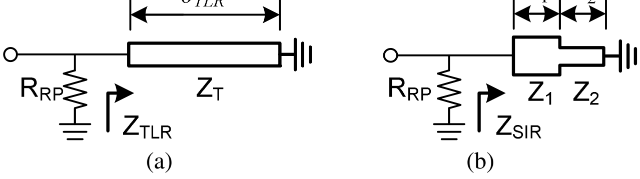
I. INTRODUCTION

In a specific band of frequency with signal absorption or attenuation condition, 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 as the NGD [1][2]. The negative group delay (NGD) concept had little use in a radio frequency (RF) circuit design because of its extremely narrow bandwidth and poor input/output return loss. Researchers have been investigating some topologies for the NGD and found some useful practical applications in the RF circuit design. In the early stage, the NGDC typically consists of the lumped element *LC* (inductor-capacitor) resonator loaded with the termination resistor [3]-[6]. Due to the limited feasibility of the lumped element circuits, the NGDC with the distributed element topology was proposed [7]. Applicability of NGDC to a signal cancellation loop that deals with signals with arbitrary waveform in time domain is discussed in [8]. 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 is also successfully applied to an analog RF feedback amplifier to increase the distortion cancellation bandwidth [10]. However, even in a product form implemented by a commercial 3 dB hybrid coupler, the NGDC of the distributed element topology occupies a large area due to the /4-transmission line resonator.

To reduce the size of the circuit, the NGDC with the SIR is proposed in this paper. From the conventional transmission line resonator, an equivalent SIR with reduced size is derived. To validate the derivation, the reflection coefficient and group delay response are compared between the two types of the one-port NGDC. Finally, the reflection type NGDC using the SIR is fabricated and tested.

II. THEORY

Fig. 1 (a) shows the schematic diagram of the reflective parallel (RP) one-port NGDC using a transmission line resonator. And its SIR equivalence is shown in Fig. 1(b). Transmission line resonators are widely used because of their simple structure and easy-to-design features. In practical design, however, such resonators have a number of intrinsic disadvantages, such as the limited design parameters due to their simple structure and spurious responses at integer multiples of the fundamental frequency [11]. The SIR was proposed to overcome those problems. The typical features of SIR are summarized as follows: (1) a wide degree of freedom, (2) derivation of generalized concept for transmission line resonators, (3) development of an expanded concept for nonuniform impedance resonators, (4) size reduction, and (5) spurious reduction [12].



(a) (b)

Fig. 1. Schematic diagram of the reflective parallel one-port NGDC using: (a) transmission line resonator, and (b) stepped impedance resonator.

The ratio of the impedance step by Z_1 and Z_2 is defined as *m,* which can be expressed using the resonance condition as follows [12]:

$$
\begin{aligned}
m &= \frac{Z_2}{Z_1} \quad , \qquad (1) \\
&= \tan\theta_1 \tan\theta_2
\end{aligned}
$$

where θ_1 and θ_2 refers to the electrical length of each stepped impedance section Z_1 and Z_2. The total electrical length (θ_{SIR}) is equal to the sum of θ_1 and θ_2. The minimum electrical length can be derived as follows:

$$
(\theta_{\mathrm{SIR}})_{\min} = \tan^{-1}\left(\frac{2\sqrt{m}}{1-m}\right), \qquad (2)
$$

where $_1$= $_2$=tan^{-1}(m) and m should be smaller than 1 for the size reduction. The size reduction factor S_R can be defined as the ratio of the electrical length of the transmission line resonator and the SIR:

$$
S_R = \frac{\theta_{SIR}}{\theta_{TLR}}. \qquad (3)
$$

As a design example, we set the goal to design a one-port NGDC at 2.14 GHz. To reduce the size, we chose m=0.4, Z_1=100 and Z_2=40 for practical fabrication. Calculated θ_{SIR} is 65°. In case of the /4 transmission line resonator, the estimated size reduction ratio when converted to the SIR is 72 % from the original size. Higher m can result in more size reduction, but unwanted parasitic effect can also occur at the step junction of transmission line due to the large impedance steps.

To validate the conversion theory, we simulated the one-port NGDC circuit shown in Fig. 1 using Agilent's ADS2009. Fig. 2 shows the simulated magnitude of the complex reflection coefficients of the one-port NGDC with the transmission line resonator and SIR. For the whole frequency band of interest, the two resonators are similar in real and imaginary reflection coefficients and slope parameters, although the latter is not shown here.

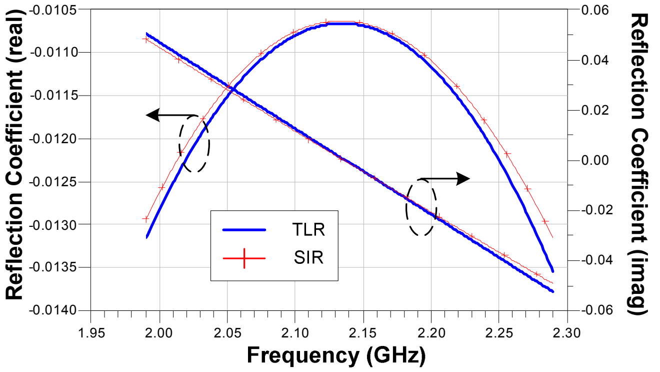


Fig. 2. Magnitude of the complex reflection coefficient of the one-port NGDC with the transmission line resonator and stepped impedance resonator.

Fig. 3 and Fig. 4 show the simulated group delay response of the one-port NGDCs. Fig. 3 represents the narrowband NGD characteristic, and the peak NGD value at the center frequency are 9.0 ns and 8.8 ns for the TLR-loaded NGDC and SIR-loaded NGDC, respectively. From Fig. 4 that shows the harmonic response of the NGD, the one-port NGDC with transmission line resonator has its intrinsic spurious response at the 3rd harmonic frequency, 6.42 GHz (3f_0) in this case. This spurious response may cause an unwanted operation when the NGDC is integrated into a system. However, in case of the one-port NGDC with the SIR, the spurious response is not observed at the 3rd harmonic frequency but it is observed at much higher frequency around 9.7 GHz (about 4.5f_0) in this case. This property is obtained due to the impedance step and the separated electrical length of the SIR.

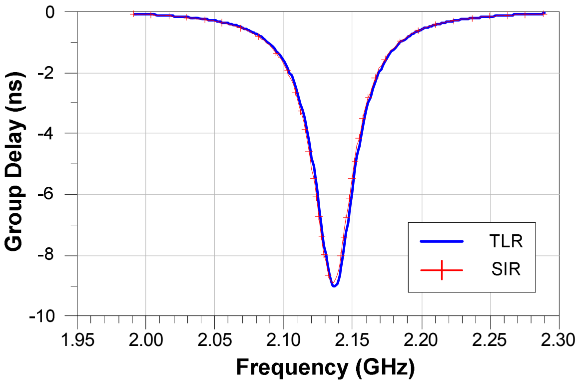


Fig. 3. Simulated in-band group delay response of the one-port NGDC with the transmission line resonator and stepped impedance resonator.

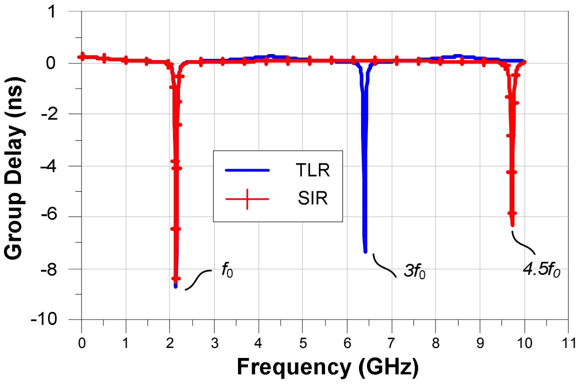


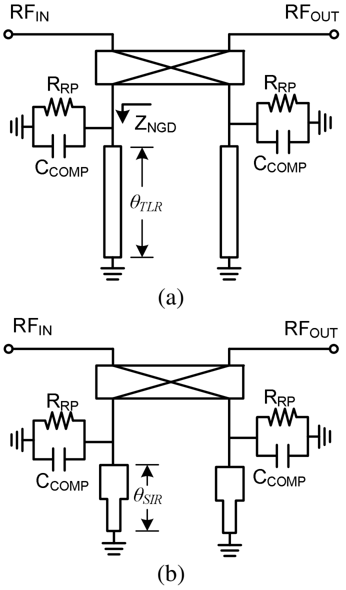
Fig. 4. Harmonic group delay response of the one-port NGDC with the transmission line resonator and stepped impedance resonator.

III. DESIGN OF THE SIZE-REDUCED NEGATIVE GROUP DELAY CIRCUIT

Based on the analysis result of the one-port NGDC, we designed two types of NGDC with the reflection topology by using Agilent's ADS2009, as shown in Fig. 5. The circuit consists of a 90° hybrid coupler which is a commercial SMD component, termination resistor (R_{RP}), compensation capacitor (C_{COMP}), and the microstrip resonators (TLR or SIR).

The transmission line resonator is typically designed to have an electrical length of 90°. The RF signal applied to RF_{IN} port is divided into coupling/through ports and attenuated by the termination resistor of which the value is R_{RP}<50 to obtain the NGD in the reflective parallel NGDC structure [7]. C_{COMP} is used to compensate the parasitic inductance of the commercial chip resistor. The stepped impedance resonator has an electrical length of 65°, which is 72% of its original size.

Fig. 6 shows the simulation results of the circuits with reflection topology shown in Fig. 5. The proposed size-reduced NGDC with the SIR has almost same characteristics as the NGDC with transmission line resonator. The simulated NGD and the signal attenuation at the center frequency are -8.5 ns and 33 dB, respectively. This signal attenuation has been shown to be easily compensated with a general purpose small signal amplifier without any stability issues when integrated into RF systems [8].



(a)

(b)

Fig. 5. Two reflection type NGDC topologies: (a) NGDC with transmission line resonator and (b) size reduced NGDC with stepped impedance resonator. $_{TLR}$=90° and $_{SIR}$=65°.

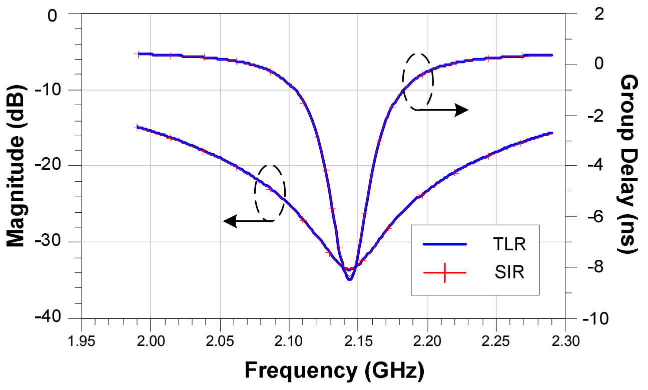


Fig. 6. Comparison of the simulated insertion loss and group delay of the NGDC with transmission line resonator and NGDC with stepped impedance resonator.

IV. EXPERIMENTAL RESULTS

For experimental verification, we have implemented the both types of the NGDC with transmission line resonator and the SIR shown in Fig. 5 at the center frequency of 2.14 GHz. Fig. 7 and Fig. 8 show the measured return loss, insertion loss, and group delay response. For the NGDC with the transmission line resonator, the measured return loss, insertion loss, and group delay response are 28 dB, 34 dB, and -9.3 ns, respectively. For the NGDC with the SIR, the measured return loss, insertion loss, and group delay response are 26 dB, 33 dB, and -8.9 ns. A little difference in the performance is due to the resistance deviation of the commercial chip resistors connected in parallel to obtain R_{RP}<50 .

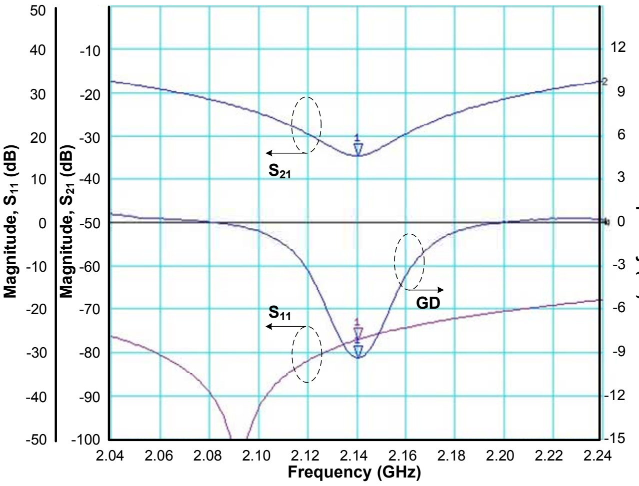


Fig. 7. Measured insertion loss, return loss, and group delay response of the NGDC with transmission line resonator.

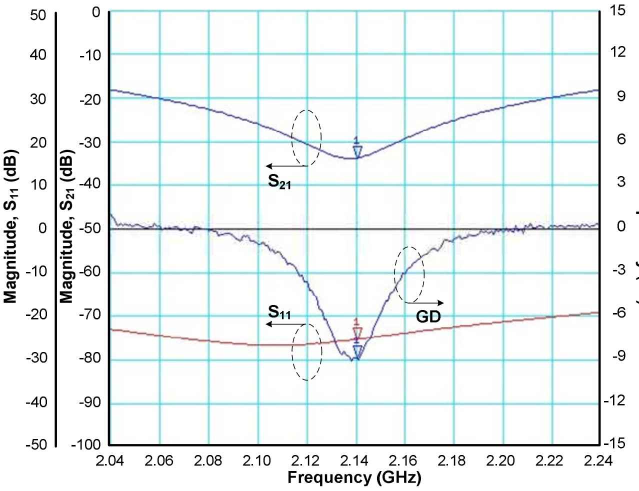


Fig. 8. Measured insertion loss, return loss, and group delay response of the NGDC with stepped impedance resonator.

Fig. 9 shows photographs of the NGD branch from the fabricated NGD circuits with the transmission line resonator and SIR. Additional capacitors are compensating capacitors (C_{COMP}) to eliminate the parasitic inductance of the chip resistor. Physical lengths of the transmission line resonator and SIR are 26.1 mm and 19.1 mm, respectively. The size reduction factor (S_R) is 73 %, which means the size is reduced to 73% from its original size.

(a) (b)

Fig. 9. Photograph of the NGD circuits of reflection topology using : (a) transmission line resonator, and (b) stepped impedance resonator.

V. CONCLUSION

In this paper, new design method to reduce the size of the planar negative group delay circuit is proposed by using a stepped impedance resonator concept. From the conventional transmission line resonator, an equivalent stepped impedance resonator with reduced size is derived. To validate the derivation, the reflection coefficient and group delay response are compared between the two types of one-port NGDC. Finally, the reflection topology NGDC using the stepped impedance resonator is fabricated and the proposed size reduction method is experimentally validated. Maintaining its intrinsic electric properties, a total size of the circuit is reduced to 73% from its original size.

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