Cascaded Reflection Type Group Delay Controller With a Wideband Flat Group Delay

Gisung Yang, *Student Member, IEEE,* Donghyun Lee, and Byung-Wook Min *Member, IEEE,*

***Abstract*—This letter presents a wideband group delay controller (GDC) based on cascaded reflection type phase shifters. Frequency tunable resonators are used as the reflective loads of each phase shifter so that the phase shifter has a variable group delay resulting in a reflection type GDC (RTGDC). Two RTGDCs with different types of the reflective loads are cascaded to compensate for their group delay variation over frequency. The first and the second stage of the cascaded RTGDC are respectively in charge of the delay in low and high frequency bands and the cascaded delay is flat over a wide bandwidth. The proposed cascaded RTGDC operates at 3.7 GHz over 200-MHz bandwidth. The measured group delay varies from 0.67 ns to 2.18 ns, which is 1.51-ns group delay variation under 9.1% normalized group delay variation over the bandwidth. The return loss is over 18 dB and insertion loss is 2.1±1.3 dB at 3.7 GHz.**

***Index Terms*—Group delay controller (GDC), large delay variation range, reflection type phase shifter (RTPS), resonator, varactor diode, wide bandwidth.**

I. Introduction

DELAY circuits to control the delay of a network have been widely used for in-band full duplex radio (FDR) system currently attracting attention to solve radio frequency congestion. The biggest challenge in FDR is cancelling self-interference (SI) signals which is changing with their environment. To cancel ever-changing SI, a tunable delay circuit needs to have a wide operation bandwidth, large group delay variation range and fine tuning resolution [1]–[4].

There are two types of tunable delay circuits, true time delay (TTD) and group delay controller (GDC). TTDs are composed of a transmission line or its equivalent for the delay elements, and have a large bandwidth. Due to the transmission line, TTDs occupy very large area to achieve either a long delay or a fine resolution [5]–[8]. GDCs, however, can make a large delay variation and a fine resolution in a small size over a limited operation bandwidth because it does not require bulky transmission lines. The bulky TTD in a system can be replaced with a GDC and a phase shifter for a given bandwidth.

Recently, various GDC structures are reported [9]–[15]. Tunable dispersive delay line (TDDL) based GDCs have a broad impedance matching bandwidth, but can provide a narrow delay variation range [9], [10]. Delay sum GDCs are recently proposed, which adjust the weight of signals through two delay lines by variable power divider and combiner [11], [12]. Although the delay variation range can be larger than that of the TDDL GDCs, it is not possible to enlarge the delay variation range over the delay of the transmission line-based delay element. A reflection types GDC (RTGDC) is similar with a reflection type phase shifter with resonator based reflective loads which can make a large delay variation in a small size, but has a large insertion loss variation and a very narrow bandwidth due to the resonator based delay [13]–[15].

For a small size and low-loss GDC with a wide bandwidth, this letter proposes a cascaded RTGDC structure combining two different RTGDCs which have a symmetrical delay response about center frequency and compensate for the delay variation of each other to have a flat group delay over a bandwidth. The structure and principle of the proposed cascaded RTGDC are explained in section II, and the reflective load

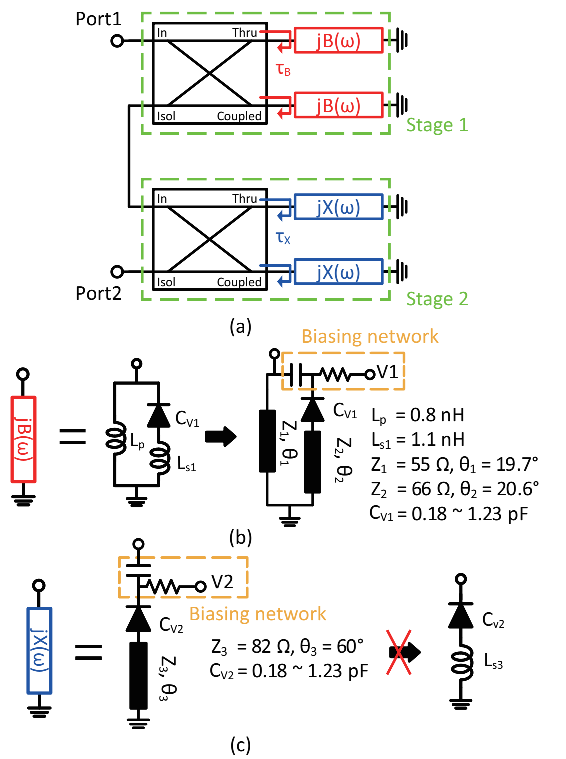

Fig. 1. Proposed (a) cascaded RTGDCs and their reflective loads of (b) the first stage (parallel resonator) and (c) the second stage (series resonator).

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The authors are with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: bmin@yonsei.ac.kr).

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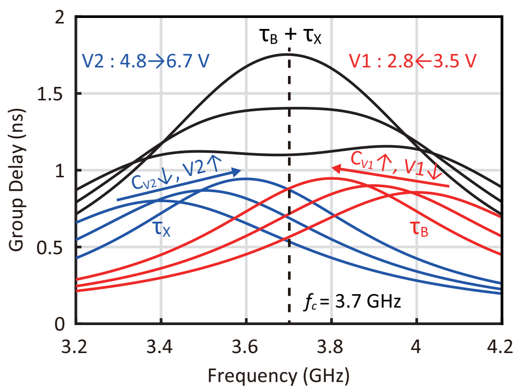

Fig. 2. Simulated delay of the first (τ_B) and second (τ_X) stages and the cascaded delay (τ_B+τ_X) of reflective load using a spice model of varacters.

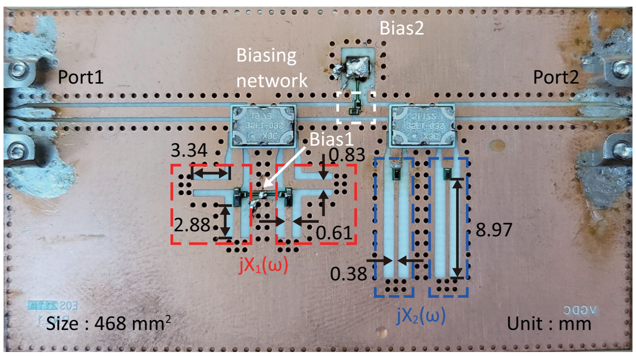

Fig. 3. Photograph of the proposed cascaded RTGDC.

design method is explained in section III, followed by the measured results and the comparison with other GDCs.

II. Cascaded Group Delay

The delay of a RTGDC is related to the reflection phase response of the reflective loads [13]–[15]. The delay of each RTGDCs in Fig. 1 is equal to the sum of the reflection delay (τ_B and τ_X) of the reflective load, $jB(\omega)$ and $jX(\omega)$ and the intrinsic delay of the hybrid coupler. Because the intrinsic delay of a hybrid coupler is flat over the coupler's operating bandwidth, the reflection delay, τ_B and τ_X only needs to be considered when designing the delay of a RTGDC. The delay of resonator based reflective load, τ_B and τ_X is the longest at the resonant frequency and can be reduced by moving away from the resonant frequency as shown in Fig. 2. By changing the resonant frequency of the reflective load, τ_B and τ_X at a center frequency (f_c) can be controlled. However, the desired τ_B and τ_X is achieved only at a single frequency resulting in a narrowband RTGDC.

The bandwidth of the RTGDC can be expanded by cascading two RTGDCs as shown in Fig. 1. The delays of two stages, τ_B and τ_X, and the cascaded delay, τ_B+τ_X are shown in Fig. 2. In order for the cascaded delay to be flattened over a wide bandwidth, τ_B and τ_X needs to be symmetric each other about f_c, which requires a similar resonator quality factor of the two different reflective loads. These characteristics of reflective loads should be maintained even when τ_B and τ_X are changed by controlling their resonant frequencies as shown in Fig. 2.

III. Resonator Based Reflective Loads

The symmetricity of the delays, τ_B and τ_X can be achieved with the reflective delays of parallel and series resonators respectively. If the reflective load, $jB(\omega)$ is a parallel resonator, the delay τ_B can be written as

$$\tau_B = \frac{2}{Y_0} \times \frac{\partial B}{\partial \omega}, \tag{1}$$

where Y_0 is termination admittance. If $jB(\omega) = 1/j\omega L + j\omega C$ is the parallel LC resonator, at $\omega_r = 1/\sqrt{LC}$

$$\tau_B|_{\omega=\omega_r} = \frac{4C}{Y_0}. \tag{2}$$

By increasing the capacitance of a parallel LC resonator, ω_r decreases while τ_B at ω_r increases as Fig. 2. To expand the admittance variation of the varactor, C_{V1}, the series inductor, L_{s1} compensate for the minimum of C_{V1} as Fig. 1(b). The inductors, L_p and L_{s1} are designed with high impedance transmission lines.

In the case of series resonator, the dual of the parallel resonator, the delay τ_X of reflective load, $jX(\omega)$ can be written as

$$\tau_X = \frac{2}{Z_0} \times \frac{\partial X}{\partial \omega}, \tag{3}$$

where the Z_0 is termination impedance. If $jX(\omega) = j\omega L + 1/j\omega C$ is the series LC resonator, at $\omega_r = 1/\sqrt{LC}$

$$\tau_X|_{\omega=\omega_r} = \frac{4L}{Z_0}. \tag{4}$$

By changing the capacitance of a series resonator, τ_X is constant even with the variation of ω_r. To make τ_X as Fig. 2, the resonator should be consisted of a transmission line instead of the inductor as shown in Fig. 1(c). Then, $jX(\omega) = jZ_3 tan(\omega\theta_3/\omega_c) + 1/j\omega C$ and $jX(\omega_r) = 0$ gives

$$\begin{aligned}\tau_X|_{\omega=\omega_r} &= \frac{2}{Z_0}\left(\frac{\theta_3 Z_3}{\omega_c} sec^2\frac{\theta_3\omega_r}{\omega_c} + \frac{1}{\omega_r^2 C}\right)\\ &= \frac{2}{Z_0}\left(\frac{\theta_3 Z_3}{\omega_c} sec^2\frac{\theta_3\omega_r}{\omega_c} + \frac{Z_3}{\omega_r} tan\frac{\theta_3\omega_r}{\omega_c}\right),\end{aligned} \tag{5}$$

which increases with ω_r since $sec^2(x)$ and $tan(x)/x$ are increasing functions for $x = \theta_3\omega_r/\omega_c < 90°$. Therefore τ_X of the transmission line based series resonator has the higher delay with the higher resonance frequency as Fig. 2.

To make τ_B and τ_X symmetric to f_c, Q factor should be similar to each other. Delay range and flatness have a trade-off relationship, so an appropriate Q factor should be selected. In order to have delay range about 1.5 ns (more than $5\lambda_c$ at $f_c = 3.7$ GHz), transmission line parameters were adjusted as shown in Fig. 1(b), (c). The reflective delays, τ_B and τ_X from $jB(\omega)$ and $jX(\omega)$ act symmetrically about f_c even when changing the delays by controlling C_{V1} and C_{V2} as Fig. 2. The delay flatness is evaluated by normalized delay variation (NDV) [8], which is

$$NDV = \frac{max(\tau_{ERR})}{\tau_{tot}} \times 100\% \tag{6}$$

where τ_{ERR} is the absolute group delay error over a bandwidth for each state and τ_{tot} is the total variable group delay.

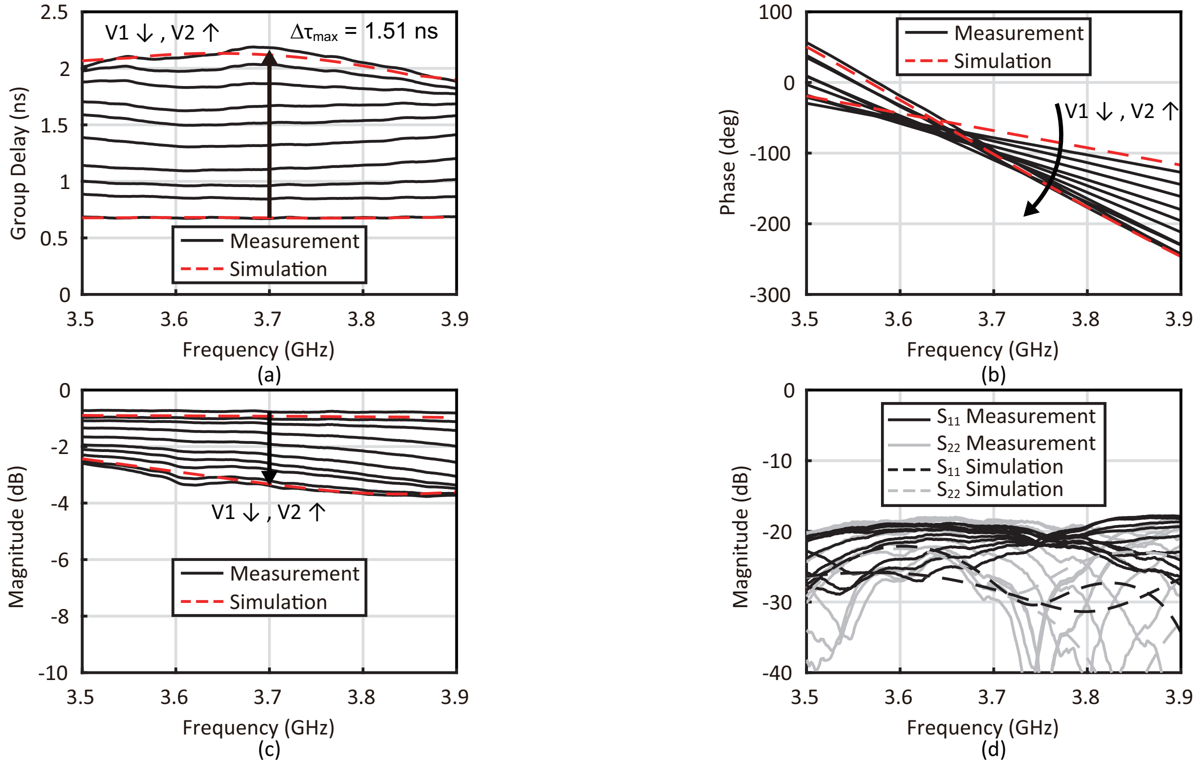

Fig. 4. Measured results of the proposed cascaded RTGDC : (a) group delay, (b) insertion phase, (c) insertion loss, (d) return loss. The bias voltages, V1 varies from 2.5 to 15 V and the V2 varies from 0 to 7 V

IV. Measurement

The photograph of the designed cascaded RTGDC is shown in Fig. 3. The proposed cascaded RTGDC is implemented on a Rogers RO4003C substrate with 0.508 mm thickness using two quadrature hybrid coupler (X3C35F1-03S) and four varactors (MAVR-000120) with DC blocks for two different DC biases.

The group delay of the RTGDC is measured with 100-MHz aperture and, as shown in Fig. 4(a), varies from 0.67 ns to 2.18 ns for 9.1% NDV over 200-MHz bandwidth at 3.7 GHz, which gives 1.51-ns group delay variation range, identical to $5.6\lambda_c$ delay. The measured insertion phase in Fig. 4(b) shows the insertion phase variation of 31.4° at 3.7 GHz, which is 9.1° RMS phase variation. The insertion loss is 2.1±1.3 dB as in Fig. 4(c), which increases when the proposed cascade RTGDC is controlled to have a larger delay. Return losses are more than 18 dB across the bandwidth for all delay states as shown in Fig. 4(d).

The comparison with other reported GDCs are shown in Table I. To compare the GDCs with different operating frequency and bandwidth, a figure of merit (FoM) is introduced with considering the fractional bandwidth (FBW), delay range, NDV, f_c, and the worst case insertion loss (I.L.)

$$FoM = \frac{FBW\ (\%) \times Delay\ range\ (sec) \times f_c\ (Hz)}{NDV\ (\%) \times I.L.\ (dB)}, \quad (7)$$

where $Delay\ range \times f_c$ is the delay range in λ_c. The most noticeable feature of this work is that it provides not only the large delay variation range but also the wide operation bandwidth with a low NDV, resulting in the highest FoM.

TABLE I
Performance Comparison with Other GDCs

Reference	I.L. (dB)	f_c (GHz)	FBW (%)	Delay range (ps)	NDV† (%)	FoM (λ_c / dB)
This work	2.1 ±1.3	3.7	5.4	1510, $5.6\lambda_c$	9.1	975×10^{-3}
[9]	1.3 ±0.5	2.5	2	265, $0.7\lambda_c$	28.8	26×10^{-3}
[10]	5.0 ±1.3	31	6.5	28, $0.9\lambda_c$	4.3	208×10^{-3}
[12]	2.2 ±0.3	2.5	12	430, $1.1\lambda_c$	22.8	226×10^{-3}
[13]	1.7 ±1.0	0.911	0.7	3000, $2.7\lambda_c$	12.6	56×10^{-3}
[15]	4.6 ±3.0	2.14	2.8	3000, $6.4\lambda_c$	15.2	156×10^{-3}

NDV† : Estimated NDV from the measured graph

V. Conclusion

A new GDC with a wide operation bandwidth and a large delay variation range are developed. The proposed GDC is based on the reflection type phase shifter with resonator based reflective loads and two complementary RTGDCs are cascaded to expand the flat delay bandwidth. The first and the second stage of the RTGDC are in charge of delays at low and high frequencies respectively with a symmetrical controllability about f_c. The designed cascaded RTGDCs have 1.51-ns group delay variation range and wide operation bandwidth from 3.6 GHz to 3.8 GHz for 9.1% NDV with the insertion loss of 2.1±1.3 dB, resulting in the highest FoM.

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