A Tunable Group Delay Circuit for Time Delay Matching Applications in Communication Systems

Girdhari Chaudhary [#1], Sungdoo Park [#2], Yongchae Jeong [#3], Jongsik Lim [*4], Jun Lee [*5]

[#] *Division of Electronics and Information Engineering*
Chonbuk National University,
Deokjin-dong, Deokjin-gu, Jeonju, 561-756, Republic of Korea
[1] girdharic@jbnu.ac.kr
[2] psd2325@jbnu.ac.kr
[3] ycjeong@jbnu.ac.kr
[*] *Department of Electrical and Communication*
Soonchunhyang University, Asan, Chungnam, Republic of Korea
[4] jslim@sch.ac.kr
[5] darkyijun@naver.com

Abstract — **In this paper, a reflective type tunable group delay circuit (TGDC) is proposed. The proposed TGDC consists of a 3 dB 90° hybrid coupler and reflective type resonators. The design equations of the proposed TGDC have been derived using port reduction method and validated by simulation and experimental results. In order to show the validity of the proposed TGDC, the simulation and an experiment were performed for a wideband code division multiple access (WCDMA) downlink band operating at 2.11~2.17 GHz. According to the experiment, the group delay (GD) time variation of 3±0.17 ns over bandwidth of 60 MHz with an excellent flatness is obtained.**

Index Terms — **delay matching, Tunable group delay circuit, resonance circuit, varactor diode.**

I. INTRODUCTION

In mobile communication systems, the transmitter performance is mainly limited with nonlinearity of the power amplifiers (PAs). Many kinds of linearization technique such as digital/analog predistortion, feedforward, direct/indirect feedback, polar loop and Cartesian loop techniques have been proposed [1]-[4] in order to improve the nonlinear performance of PAs, such as intermodulation distortion (IMD), AM to AM, AM to PM, adjacent channel leakage ratio (ACLR), error vector magnitude (EVM) etc. In order to achieve broadband linearization of the PAs, the broadband GD matching as well as amplitude and out of phase matching are very important design issues. A coaxial cable or a GD bandpass filter is used for the GD matching component in conventional linear PAs.

There have been several efforts to design microwave GD control circuits [5-9]. The GD circuit proposed in [5] consists of reflection topology with series R-L-C tuned circuit reflection terminations. The GD circuit proposed in [6] changes the RF paths in order to obtain the different fixed GD times using RF switches. Park *et.al.* developed microwave GD circuit which can control the GD time, but the circuit has too narrow bandwidth and a huge circuit size [7]-[8].

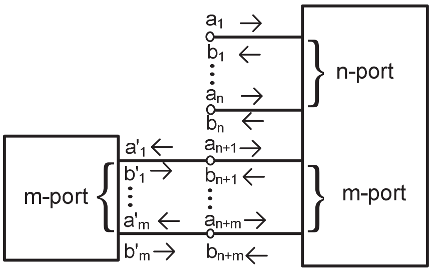


Fig. 1 Illustration of port reduction method.

Choi *et.al.* developed a narrowband feedforward linear PA using GD matching circuit, which showed the benefit of a TGDC in design and operations of a linear PA [9].

To overcome the limitations of previous GD circuits, a new broadband TGDC based on reflection topology has been proposed in this paper. The proposed TGDC uses a reflective characteristic of a parallel resonator. The design equations have been derived and experimentally validated.

II. DESIGN AND IMPLEMENTATION

To derive the general design equation for the proposed TGDC, we need to investigate the port reduction method. By terminating the m-port with a load network at the (n+m)-port, as shown in Fig.1, the new S-matrix of the reduced n-port network can be obtained as (1).

$$[S] = S'_{11} + S'_{12}\left[S_L^{-1} - S'_{22}\right]^{-1} S'_{21} \qquad (1)$$

where S_L is the S-matrix of terminated m-port load network and S'_{ii} is the S-matrix of (n+m) port network [10].

Fig. 2 shows the proposed reflective type TGDC which consists of 3-dB 90^0 hybrid coupler and LC-parallel resonators.

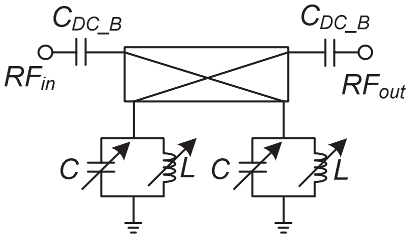


Fig. 2. Proposed reflection type tunable group delay circuit using parallel resonator.

For simplicity, 3-dB 90^0 hybrid coupler is assumed to be lossless, perfectly matched, and having infinite isolation. Since the through and coupling ports of the 3-dB 90^0 hybrid coupler are terminated with reflective type parallel resonators, the S_L-matrix of load network can be expressed as (2).

$$[S_L]=\begin{bmatrix}\Gamma_{RP} & 0\\ 0 & \Gamma_{RP}\end{bmatrix} \qquad (2)$$

The new reduced S-matrix of proposed 2-port TGDC is obtained from the 4-port S-matrix of the general 3-dB 90^0 hybrid coupler, (1) and (2), by using port reduction method described above.

The voltage reflection coefficient of the reflection termination is expressed as (3).

$$\Gamma_{RP}=\frac{(Y_0\omega L)^2-(\omega^2LC-1)^2}{(Y_0\omega L)^2+(\omega^2LC-1)^2}+j\frac{2Y_0\omega L(1-\omega^2LC)}{(Y_0\omega L)^2+(\omega^2LC-1)^2} \qquad (3)$$

Therefore, the transmission coefficient magnitude and phase of proposed TGDC is given as (4) and (5).

$$|S_{21}|=\sqrt{\left(\frac{2Y_0\omega L(1-\omega^2LC)}{(Y_0\omega L)^2+(\omega^2LC-1)^2}\right)^2+\left(\frac{(\omega^2LC-1)^2-(Y_0\omega L)^2}{(Y_0\omega L)^2+(\omega^2LC-1)^2}\right)^2} \qquad (4)$$

$$\angle S_{21}=\tan^{-1}\left(\frac{(\omega^2LC-1)^2-(Y_0\omega L)^2}{2Y_0\omega L(1-\omega^2LC)}\right) \qquad (5)$$

The GD is a measure of the slope of the transmission phase response. Mathematically, it is defined as a derivative of the phase variation with respect to angular frequency which is given as (6).

$$\tau=-\frac{d\angle S_{21}}{d\omega} \qquad (6)$$

Therefore, GD of the proposed circuit is obtained using:

$$\tau\Big|_{\omega=\omega_0}=-\frac{d\angle S_{21}}{d\omega}\Big|_{\omega=\omega_0}=\frac{4}{Y_0\omega_0^2L}=4Z_0C \qquad (7)$$

where Z_0 is the characteristics impedance.

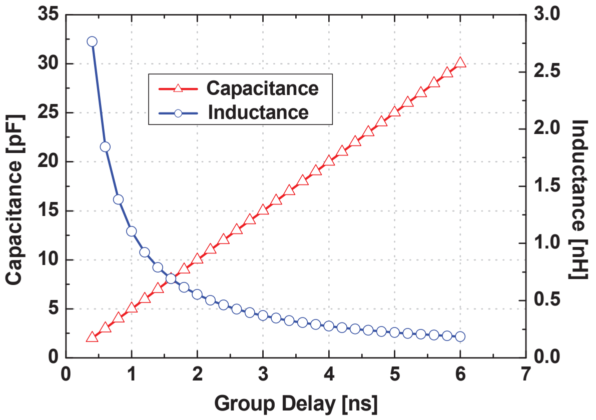
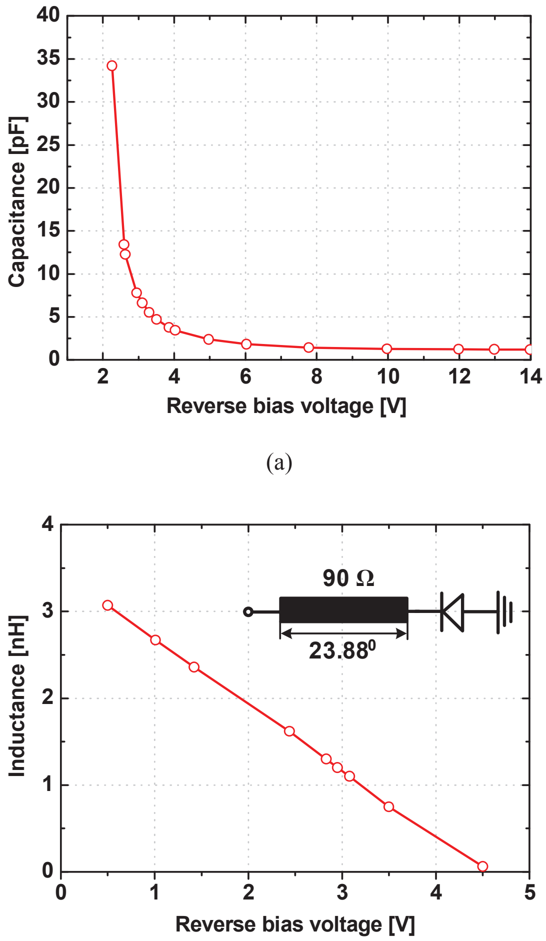


Fig. 3. Calculated value of capacitor and inductor for specific group delay at operating frequency 2.14 GHz.



(a)

(b)

Fig. 4. Measurement result of (a) varactor diode (b) variable inductor at operating frequency 2.14 GHz.

From (7), it is clear that the GD is inversely proportional to the inductance or proportional to the capacitance at a constant resonance frequency.

The GD time variations can be obtained by varying the inductance and capacitance assuming a resonance condition at desired operating frequency. Fig. 3 shows the calculated capacitance and inductance to obtain specific GD times at operating frequency. The required variable capacitance in this work was implemented with varactor diodes SMV1233-011LF of skyworks, by controlling reverse bias voltage.

Similarly, the required variable inductor was obtained with high impedance transmission line terminated with the varactor diode. Fig. 4 (a) and (b) show the measurement results of varactor diode and variable inductor at 2.14 GHz. In this work, a 90 Ω high impedance transmission line with electrical length of 23.88° is used to obtain the required variable inductance.

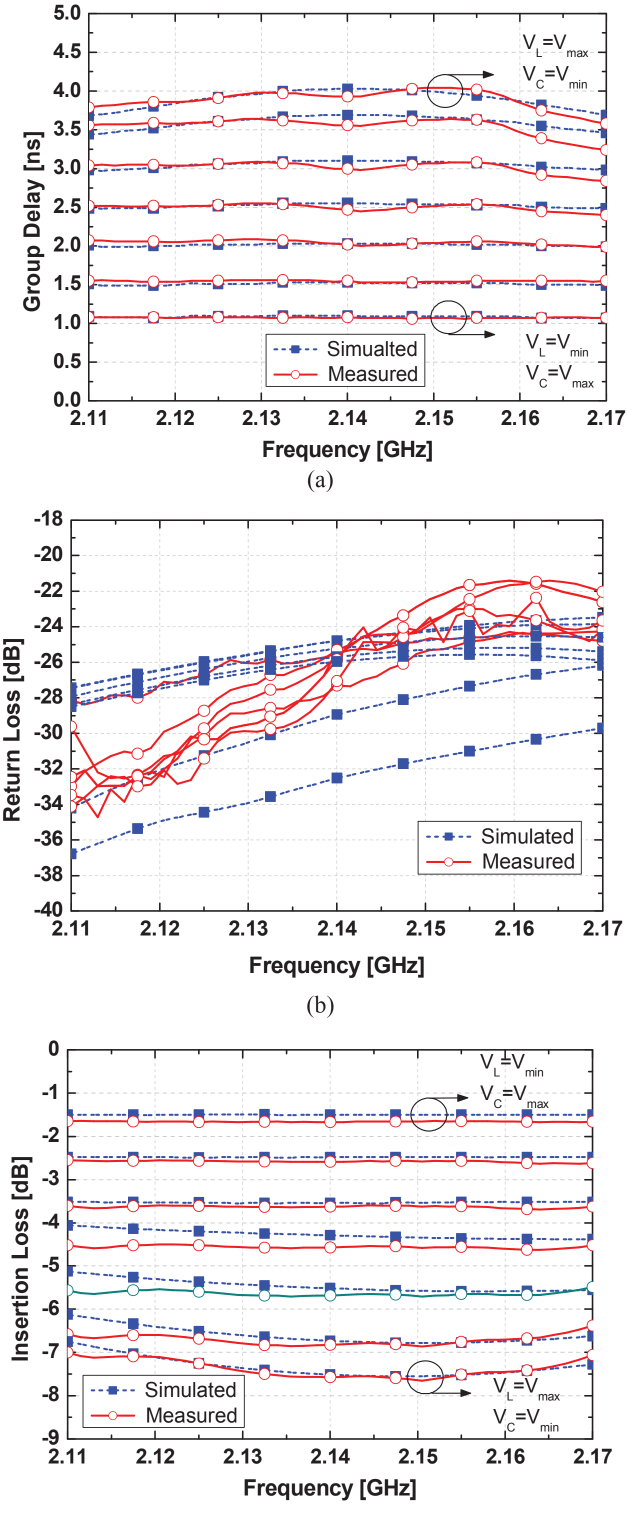
III. SIMULATION AND EXPERIMENTAL RESULTS

To show the validity of proposed TGDC, the simulation and experiment was performed for the WCDMA downlink band operating at 2.11~2.17 GHz. Fig. 5 (a), (b) and (c) show the simulated and measured GD time variation, the insertion loss and return loss characteristic, respectively. The simulated GD time and insertion loss variation are 3±0.16 ns and 5.9 dB with an excellent flatness of 0.5 dB, respectively. The maximum return loss is 23.86 dB in the passband for overall GD time variation range.

From the experiment, GD variation of 3±0.17 ns over 60 MHz bandwidth with excellent flatness is obtained. The insertion loss variation is about 6 dB, which is due to high variation of the junction resistance in the varactor diode according to control voltage variation. The insertion loss variation can be easily compensated with an automatic gain control amplifier in the linear PA system. The insertion loss flatness is less than 0.57 dB at fixed GD and maximum return loss is 21.18 dB in the passband for the overall GD variation. The reserve bias voltage variations of the varactor diodes for inductance and capacitance are 0.01~3.53 V and 3.69~13.18 V respectively.

Table I.
The Performance comparisons of the proposed TGDC

	Frequency [MHz]	GD Variation [ns]	Bandwidth [MHz]
[7]	869-894	1	25
[8]-[9]	908.5-914	3	5.5
This work	**2110-2170**	**3**	**60**



(a)

(b)

(c)

Fig. 5. The simulated and measured: (a) group delay time variation (b) the return loss characteristics and (c) the insertion loss characteristics. The reserve bias voltage variation: V_L=0.01~3.53 V and V_C= 3.69~13.18 V.

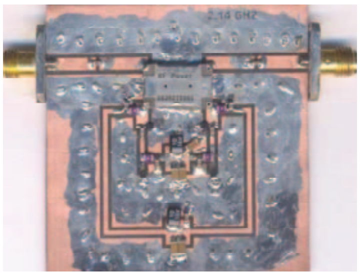


Fig. 6. The photograph of the fabricated tunable group delay circuit.

If the insertion loss flatness higher than 0.57 dB is accepted, the larger GD time variation can obtained. So trade-off among the GD variations, insertion loss and GD flatness should be considered. A small amount of difference in simulation and measurement is due to the connecting elements at diodes.

Table I shows the performances comparison among the proposed TGDC and previous works. This work confirms that the bandwidth of the proposed TGDC is much broader than the bandwidths of the previous GD circuits. The photograph of fabricated TGDC is shown in Fig. 6.

VII. CONCLUSION

In this paper, a reflective tunable group delay circuit consisting of a 3-dB 90° hybrid coupler and reflective parallel resonators has been proposed. The general design equation of the proposed tunable group delay circuit is derived by using the port reduction method. The proposed tunable group delay circuit was fabricated and measured for the wide-band code division multiple access base-station downlink frequency operating at 2.11~2.17 GHz. The group delay time and insertion loss flatness are excellent within the operating band.

The proposed tunable group delay circuit experimentally achieved the broadest bandwidth among the previously reported group delay circuits in the literature with additional advantages as to its size and its cost reduction. The proposed broadband tunable group delay circuit is expected to play an important role in broadband communication systems where critical group delay time matching is required.

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