A Novel Design for a Dual-Band Negative Group Delay Circuit

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***Abstract*—In this letter, a novel design for a dual-band negative group delay circuit (NGDC) is proposed. Based on the topology of a single-band reflection type NGDC, composite right/left handed $\lambda/4$ short stubs are employed to obtain a negative group delay (NGD) at two separate frequency bands simultaneously. In order to achieve a bandwidth extension, the proposed structure consists of a two-stage dual-band NGDC with different center frequencies connected in a cascade. According to the measurements performed for wide-band code division multiple access and worldwide interoperability for microwave access, an NGD of −3.0± 0.4 ns and −3.1± 0.5 ns are obtained at 2.12–2.16 GHz and 3.46–3.54 GHz, respectively.**

***Index Terms*—Composite right/left handed (CRLH), dual-band, negative group delay (NGD), wide-band code division multiple access (WCDMA), worldwide interoperability for microwave access (WiMAX).**

I. Introduction

In the process of the rapid evolution into the ubiquitous communication environment, the demands for multi-band mobile/base-station devices capable of adapting to multiple wireless communication platforms have increased considerably [1], [2].

Recently, some interesting studies of the negative group delay (NGD) concept have led to its experimental validation through the realization of its electronic circuit. In a specific and narrow frequency band of signal attenuation 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 NGD. Experimental validations of the theoretical analysis about those phenomena have been presented in previous studies [3]–[5]. In the early stage, the NGD concept had little use in 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 radio frequency (RF) circuit design [6]–[11]. Negative group delay circuit (NGDC) has been successfully employed to an analog feed-forward amplifier in wide-band code division multiple access (WCDMA) band to improve the overall system efficiency [9]. General synthesis equations and the planar circuit implementation technique with good input/output return loss were proposed in [10]. Dual-band NGD topology was proposed in [11], but the NGD could be obtained only at the specific frequencies without any bandwidth flatness. Based on the result obtained in [9]–[11], we set our goal to extend the application of NGDC to dual-band operation for WCDMA and WiMAX base-station.

In this letter, a novel dual-band NGDC with an extended bandwidth is proposed. First, we will explain the principle theory for the NGD property. Second, the proposed circuit topology is described in detail. Finally, the comparison of the one-stage and two-stage dual-band NGDCs are discussed in terms of bandwidth flatness and commercial applicability.

II. Dual-Band Negative Group Delay Circuit

In the medium of the refractive index $n\ (\omega)$, the dispersion relation can be written as [5]

$$\kappa = \frac{\omega n}{c} \tag{1}$$

where κ is the wave number and c is the speed of light. The group velocity (v_g), meaning the speed of the envelope signal, is then given by [5]

$$v_g = \frac{c}{n + \omega \mathrm{Re}[dn/d\omega]}. \tag{2}$$

From the above equation, it can be inferred that if the refractive index decreases rapidly according to the frequency, the group velocity can become negative. This event does happen near an absorption line or in media with signal attenuation, where anomalous wave propagation effects can occur [5]. Typically, in an RF circuit design based on a dielectric laminate, we cannot control the refractive index of the given material. But it is possible to obtain an NGD through deliberate resistive signal attenuation. Additionally, the attenuation can be easily compensated with a small signal gain amplifier without reducing total NGD.

The main goal of this work is to design a dual-band NGDC for the WCDMA downlink band (2.14 ± 0.02 GHz) and the WiMAX band (3.50 ± 0.04 GHz). A circuit diagram of the proposed dual-band NGDC is illustrated in Fig. 1. The proposed circuit consists of a broadband 3 dB 90° hybrid coupler to fully cover the two frequencies (2.14–3.5 GHz) [12], and a termination resistor R_{RP} that is loaded with the composite right/left handed (CRLH) $\lambda/4$ short stub for dual-band operation. To increase the bandwidth flatness for a practical applica-

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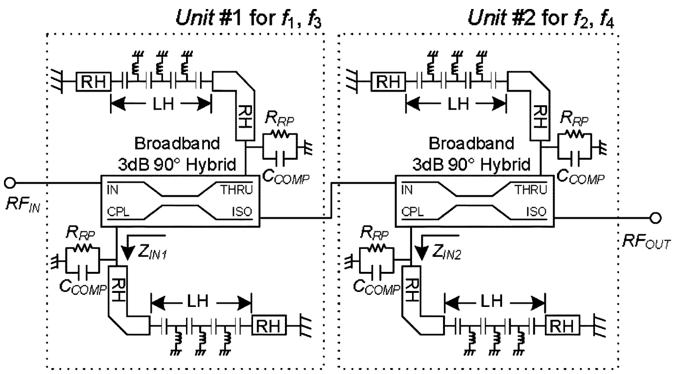

Fig. 1. Circuit diagram of the proposed two-stage dual-band NGDC.

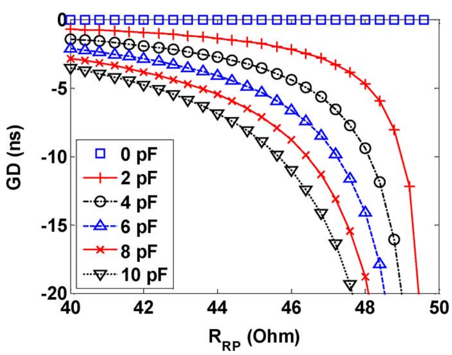

Fig. 2. Calculated group delay according to R_{RP} and C_{RP}.

tion, two-stages of dual-band NGDCs with different frequencies of operation are cascaded, as shown in Fig. 1. If we assume f_1, f_2, f_3, and f_4 as 2.12, 2.16, 3.46, and 3.54 GHz, respectively, unit #1 should have a dual-band operation for f_1 and f_3, and unit #2 should have a dual-band operation for f_2 and f_4. The cascading of these two units produces a flat bandwidth in terms of the insertion loss and the NGD.

The condition to obtain the NGD in a reflective parallel (RP) NGDC can be expressed by the following equation [10]:

$$\tau = \left.\frac{-d\Phi_{\mathrm{in}}}{d\omega}\right|_{\omega=\omega_1,\omega_2} = \frac{4R_{\mathrm{RP}}^2 C_{\mathrm{RP}} Z_0}{R_{\mathrm{RP}}^2 - Z_0^2} \tag{3}$$

where τ is the group delay, Φ_{in} is the phase of the input impedance (Z_{IN}) at the coupling and the through port of the 90° hybrid coupler, ω_1 and ω_2 are the resonant frequencies of the CRLH $\lambda/4$ short stub, C_{RP} is the total equivalent capacitance of the CRLH $\lambda/4$ short stub, and Z_0 is the termination impedance of the broadband 90° hybrid coupler, which is 50 Ω in this case. If τ is to be negative, the R_{RP} needs to be smaller than 50 Ω. The NGD is proportional to C_{RP} and R_{RP}, as shown in Fig. 2. In Fig. 1, the coupling (CPL) and through (THRU) port of the 90° hybrid coupler needs to be terminated with R_{RP} at the resonant frequency, which implies the input impedance of the $\lambda/4$ stub needs to be open at the desired frequencies. This operation can be achieved by adapting the CRLH transmission line.

The CRLH $\lambda/4$ short stub, which is a combination of the conventional right-handed (RH) and the left-handed (LH) transmission line, as shown in Fig. 3, exhibits a dual-band response [13]. Due to the positive phase response of the LH component, the CRLH transmission line demonstrates a higher phase slope

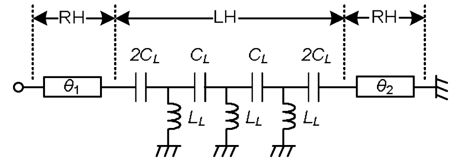

Fig. 3. Schematic of the CRLH $\lambda/4$ short stub for $\mathrm{N} = 3$. For f_1 and f_3, components' values are: $C_L = 1.8$ pF, $2C_L = 3.0$ pF, $L_L = 35°/133\ \Omega$ (short stub), and $|\theta_{RH}| = 188°$. For f_2 and f_4, $C_L = 1.7$ pF, $2C_L = 3.4$ pF, $L_L = 33°/133\ \Omega$ (short stub), and $|\theta_{\mathrm{RH}}| = 181°$.

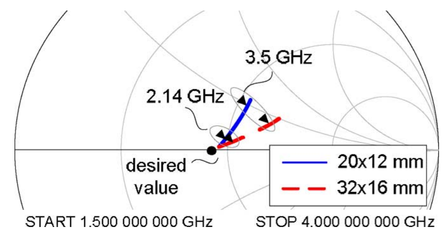

Fig. 4. Measured parasitic input impedance of the two commercial chip resistors with same value and different dimensions (20 × 12 and 32 × 16 [mm]).

than the RH line for a fixed electrical length. In other words, the electrical length of the odd multiple of $-90°(\lambda/4$ and $3\lambda/4)$ is obtainable at the odd harmonic frequencies in the case of the RH line. However, the frequency with the $3\lambda/4$ wavelength, which is the second desired frequency, can be controlled by adjusting the number of the stages of the LH unit cell (N) and the combined element values (C_L, L_L) together with the electrical length of the RH lines $(\theta_{\mathrm{RH}} = \theta_1 + \theta_2)$ within the range of $1 < f_2/f_1 < 3$.

The desired termination resistor R_{RP} can be obtained by the parallel combination of the two chip resistors. As shown in Fig. 4, however, the chip resistor in a real situation has a parasitic reactance as well as its own resistance variations over the frequency range. It is important to maintain the resistance as constant as possible over the frequency range in order to obtain a similar NGD at the two frequency bands. This is done by employing a compensating parallel capacitor (C_{COMP}). Therefore the physical size of the chip resistor needs to be as small as possible within the permissible power handling capability.

III. Experimental Results

In Fig. 5, we compare the simulated and measured results of the single stage dual-band NGDC. The dual-band NGDC shows NGDs of −4.2 ns and −3.5 ns at 2.14 GHz and 3.5 GHz, respectively. Measured result agrees well with the simulation near the center frequencies. The slight differences observed at band edges are because ideal capacitors and resistors are used in simulation, but not in realization. The time difference of 0.7 ns between the two frequencies was due to the resistance variation of the chip resistor in accordance with the frequency.

Fig. 6 shows the measured results of the two-stage dual-band NGDC. In unit #1, $C_{\mathrm{COMP}} = 0.8$ pF, $C_L = 1.8$ pF, $2C_L = 3.0$ pF, $|\theta_{\mathrm{RH}}| = 188°, L_L = 35°/133\ \Omega$ (short stub) were used in practical realization to obtain dual-band operation at f_1 and f_3. In unit #2, $C_{\mathrm{COMP}} = 0.9$ pF, $C_L = 1.7$ pF, $2\ C_L = 3.4$ pF, $|\theta_{\mathrm{RH}}| = 181°, L_L = 33°/133\ \Omega$ (short stub) were used to obtain dual-band operation at f_2 and f_4. For both units, $R_{\mathrm{RP}} = (47//500)\ \Omega$. The insertion loss and group

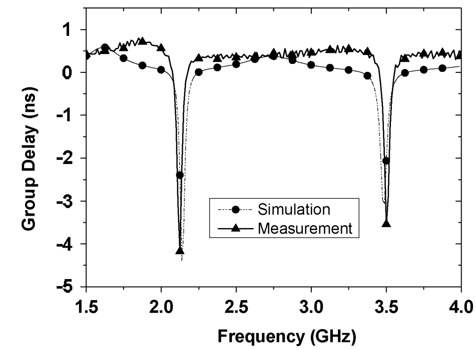

Fig. 5. Simulated and measured group delay of the single-stage dual-band NGDC.

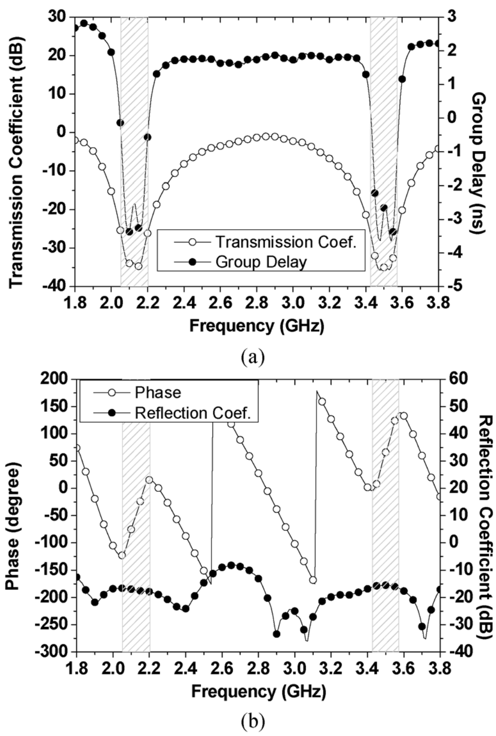

Fig. 6. Measured results of the two-stage dual-band NGDC: (a) insertion loss and group delay, and (b) phase and return loss. Phase slopes are inverted in the highlighted dual-band NGD regions.

delay are shown in Fig. 6(a), and the phase and return loss are presented in Fig. 6(b). The highlighted areas show the NGD regions. The NGD of $-3.0\pm$ 0.4 ns and $-3.1\pm$ 0.5 ns were obtained at 2.12–2.16 GHz and 3.46–3.54 GHz, respectively. The magnitude of the flatness for each band was measured as $-34.2\pm$ 0.5 dB and $-34.9\pm$ 0.7 dB, respectively. Maximum return loss was -17 dB. When compared to the reference results presented in Fig. 5, the two-stage dual-band NGDC had a much wider bandwidth, showing practical applicability.

In the NGD region, the slope of the phase is observed to be positive, implying that the group velocity is negative. Negative group velocity means that the direction of envelope propagation is opposite to the direction of the signal propagation. This inverted phase slope can be used to cancel out or control the negative phase slope (or positive GD) of a conventional circuit, consequently achieving a zero phase slope (therefore a smaller or even zero GD). For example, in case of an intermodulation distortion cancellation loop in an analog feedforward amplifier, NGDC can be used to eliminate a lossy delay element and increase the system efficiency [9]. Fig. 7 shows the photograph of the fabricated two-stage dual-band NGDC. The total size is 140×70 mm^2.

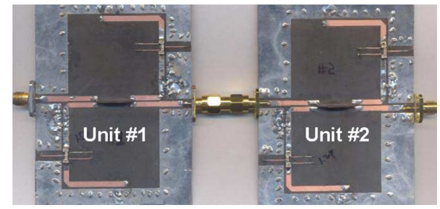

Fig. 7. Photograph of the fabricated two-stage dual-band NGDC.

IV. Conclusion

In this letter, we propose the novel design and implementation of a two-stage dual-band NGDC using a composite right/left handed transmission line. The importance of the proposed work lies in the dual-band design for the interesting NGD property. The proposed circuit is expected to be applicable to WCDMA and WiMAX base-station applications to reduce lossy output delay elements and improve efficiency of the systems.

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