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Dual-Band Negative Group Delay Circuit Using $\lambda/4$ Composite Right/Left-Handed Short Stubs

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Abstract

In this paper, a novel design for a dual-band negative group delay circuit (NGDC) is proposed. Composite right/left-handed (CRLH) $\lambda/4$ short stubs are employed as a dual-band resonator. A CRLH $\lambda/4$ short stub is composed of a typical transmission line element as the right-handed component and a high-pass lumped element section as the left-handed component. It is possible to simultaneously obtain open impedances at two separate frequencies by the combination of distinctive phase responses of the right/left-handed components. Negative group delay (NGD) can be obtained at two frequencies by using dual-band characteristics of the CRLH stub. 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 experiment performed, with wide-band code division multiple access (WCDMA) and world-wide interoperability for microwave access (WiMAX), NGDs 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.

Key words : Composite Right/Left-Handed, Dual-Band, Negative Group Delay, WCDMA, WiMAX.

Ⅰ. Introduction

In the process of the rapid evolution into a 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 on 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. A 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 regarding these phenomena have been presented in previous studies [3] ~ [5]. In the early stages, the NGD concept had little use in practical radio frequency (RF) system design because of its extremely narrow bandwidth and poor input/output return loss. Researchers have been investigating some topologies for the NGD and have found some useful practical applications in RF circuit design [6] ~ [14]. General synthesis equations and the planar circuit implementation technique with good input/output return loss were proposed in [9], [10]. A negative group delay circuit (NGDC) has been successfully employed in a signal cancellation loop to improve the time advance property [11], and to an analog feed-forward amplifier in a WCDMA band to improve the overall system efficiency [12]. NGDC was also adapted to the analog feedback linearization topology to reduce the feed-back time (the propagation time required for a signal coupled from the power amplifier output terminal that is to be transmitted through several signal adjusting devices before being injected into the input terminal) and to increase the cancellation bandwidth [13]. Dual-band NGD topology was proposed in [14], but the NGD could only be obtained at the specific frequencies without bandwidth flatness.

The CRLH transmission line (TL), which consists of a left-handed TL (LH TL) and the typical right-handed TL (RH TL) was proposed in [15], [16]. The equivalent lumped element circuit of the LH TL shows positive phase response (phase lead). However, the RH TL has a negative phase response (phase lag). These have been applied to the design of a dual-band $\lambda/4$ short stub, in which the phase response of the CRLH TL is manipulated to yield the electrical lengths of odd multiple of ±90°, at two arbitrary frequencies.

Based on the results obtained in [1] and [9] ~ [16], we

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set our goal to extend the application of NGDC to dual-band operation for WCDMA and a WiMAX base-station. First, we will explain the principals of NGD and λ/4 CRLH short stub. Second, the proposed circuit topology and operation principles are also described in detail. Finally, a comparison of the 1-stage and 2-stage dual-band NGDCs in relation to bandwidth flatness and commercial applicability is provided.

Ⅱ. Theory and Simulation

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

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

where k 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:

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

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 intentional resistive signal attenuation. Additionally, the attenuation can be easily compensated with a small signal gain amplifier, without reducing total NGD [10].

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 provided 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) [17], and a termination resistor R_{RP} that is loaded with a CRLH λ/4 short stub for dual-band operation. To increase the bandwidth flatness for a practical application, 2-stages of dual-band NGDCs with different frequencies of operation can be cascaded. 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, for example. The cascading of these two units produces a flat bandwidth in terms of the insertion loss and the NGD. In this case, signal attenuation is also increased. Therefore, careful trade-off between the NGD and insertion loss should be considered.

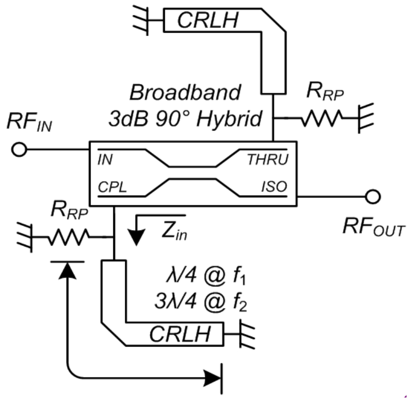


Fig. 1. Circuit diagram of the proposed 1-stage dual-band negative group delay circuit (NGDC).

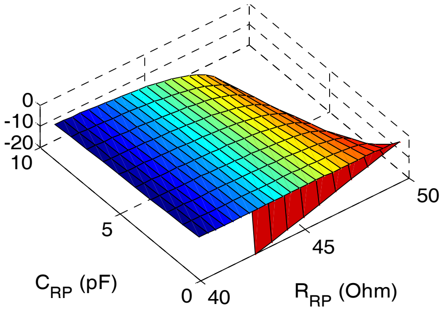


Fig. 2. Calculated group delay according to R_{RP} from 40 to 50 Ω, and CRP from 0 to 10 pF with 2 pF steps.

The condition to obtain the NGD in a reflective parallel (RP) NGDC can be expressed by the following equation [12]:

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

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 λ/4 short stub, which has dual-band characteristics, C_{RP} is the total equivalent capacitance of the lumped element equivalent circuit of the CRLH λ/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, 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 that the input impedance of the λ/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, exhibits a dual-band response [15], [16]. The phase response of a CRLH structure is expressed as (4):

$$\phi_C = \phi_R + \phi_L \approx -N\omega\sqrt{L_R C_R} + \frac{N}{\omega\sqrt{L_L C_L}}, \tag{4}$$

where ϕ_R, ϕ_L, and ϕ_C are the electrical lengths of RH, LH, and CRLH component, respectively, and N denotes the number of stages, and ω is the angular frequency. L_R and C_R denote the component values of the RH component, and L_L and C_L denote the component values of the LH component. Given N, two frequencies of operation (f_1, f_2), the desired phase responses at these frequencies (ϕ_1, ϕ_2), which are −90° and −270° in this case, and the characteristic impedance of the CRLH line (Z_0), which is typically 50 Ω, mean that the component values of the CRLH line can be obtained from the following equations:

$$L_R = \frac{Z_0\left(\frac{\phi_1}{f_2} - \frac{\phi_2}{f_1}\right)}{2\pi N\left(\frac{f_2}{f_1} - \frac{f_1}{f_2}\right)} \tag{5}$$

$$C_R = \frac{\left(\frac{\phi_1}{f_2} - \frac{\phi_2}{f_1}\right)}{2\pi N Z_0\left(\frac{f_2}{f_1} - \frac{f_1}{f_2}\right)} \tag{6}$$

$$L_L = \frac{Z_0 N\left(\frac{f_2}{f_1} - \frac{f_1}{f_2}\right)}{2\pi(\phi_1 f_2 - \phi_2 f_1)} \tag{7}$$

$$C_L = \frac{N\left(\frac{f_2}{f_1} - \frac{f_1}{f_2}\right)}{2\pi Z_0(\phi_1 f_2 - \phi_2 f_1)} \tag{8}$$

$$Z_0 = \sqrt{\frac{L_R}{C_R}} = \sqrt{\frac{L_L}{C_L}}. \tag{9}$$

Fig. 3 shows the phase response of CRLH dual-band $\lambda/4$ and RH $\lambda/4$ transmission line. Due to the positive phase response of the LH component, the CRLH transmission line demonstrates a higher phase slope than the RH line for a fixed electrical length. In other words, the electrical lengths of the odd multiple of −90° ($\lambda/4$ and $3\lambda/4$) are obtainable at odd harmonic frequencies in the case of the RH line. However, in the CRLH case, 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 parameter values (C_L, L_L) together with the electrical length of the RH lines ($\theta_{RH}=\theta_1+\theta_2$) within the range of $1<f_2/f_1<3$.

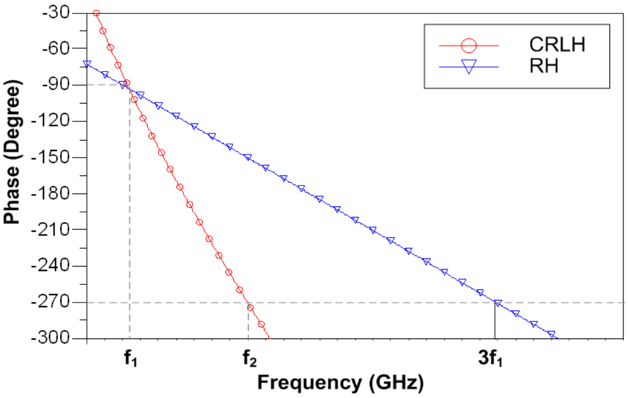


Fig. 3. Simulated phase response of the composite right/left-handed (CRLH) dual-band $\lambda/4$ and RH $\lambda/4$ transmission line.

Fig. 4 shows the schematic of the CRLH dual-band $\lambda/4$ short stub, and Fig. 5 shows the simulation and measurement results. The number of unit cells (N) for 2.14 GHz and 3.5 GHz is calculated as 3. It is validated through circuit simulation using Agilent's ADS2009 and measurement. The required circuit parameters are as follows: C_L=2.1 pF, $2C_L$=4.2 pF, L_L=30°/133 Ω (short stub), and $|\theta_{RH}|$=193° for circuit simulation, C_L=1.8 pF, $2C_L$=3.0 pF, L_L=36°/133 Ω (short stub), and $|\theta_{RH}|$=183° for measurement. Simulated and measured results were consistent, except for a slight resistance difference due to the limited quality factor of the real-world components.

Ⅲ. Experiment

The broadband 3 dB 90° hybrid coupler has been employed as a hybrid coupler to cover 2.14 GHz and 3.5

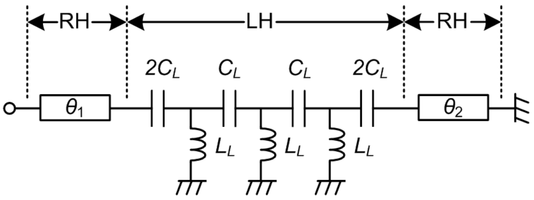


Fig. 4. The schematic of the CRLH $\lambda/4$ short stub for N=3. Component values: C_L=2.1 pF, $2C_L$=4.2 pF, L_L=30°/133 Ω (short stub), and $|\theta_{RH}|$=193° for circuit simulation, C_L=1.8 pF, $2C_L$=3.0 pF, L_L=36°/133 Ω (short stub), and $|\theta_{RH}|$=183° for measurement.

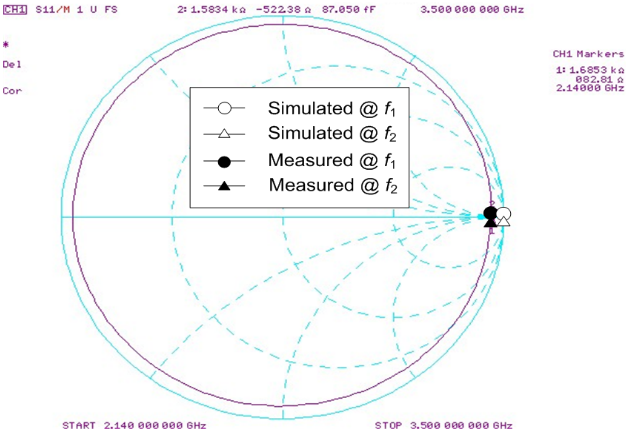


Fig. 5. Simulated and measured results of the CRLH dual-band λ/4 short stub for 2.14 GHz and 3.5 GHz.

GHz at the same time. Due to the extremely narrow coupling gap in the central coupling element, caused by too small odd impedance, the design of a 3 dB planar multi-section coupler with a broad bandwidth is a tough goal. Based on the design method proposed in [17], the broadband 3 dB 90° hybrid coupler, which covers f_1= 2.14 GHz and f_2=3.5 GHz was designed using the vertically installed planar (VIP) structure to increase the coupling area at the central coupling element.

Fig. 6 shows a photograph of the fabricated broadband 3 dB 90° hybrid coupler, and the measured results compared with the electro-magnetic (EM) wave simulation are shown in Fig. 7. The measured magnitudes of coupling and through ports are −3.10±0.2 dB and −3.18 ±0.01 dB, respectively. The maximum return loss is higher than 30 dB for 2.14/3.5 GHz. A dual-band NGDC employing the CRLH λ/4 stub and the broadband 3 dB 90° hybrid coupler is designed and implemented according to the proposed design method, and is fabricated with a microstrip line.

In Fig. 8, we compare the simulated results of the 1-stage single-band NGDC with λ/4 RH short stubs, from [10], and the dual-band NGDC, from this work. The dual-band NGDC shows NGDs of around −7 ns and −5 ns at 2.14 GHz and 3.5 GHz, respectively. The time difference of 2 ns between the two frequencies was due to the fact that the termination impedances of the designed broadband hybrid coupler are not exactly 50 Ω. When the termination impedance of the 3 dB hybrid coupler is not 50 Ω, the resulting NGD varies from the desired value, as expected in (3).

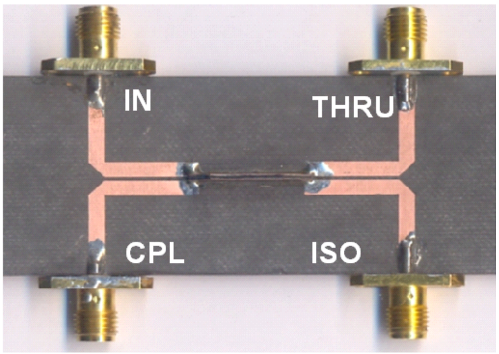


Fig. 6. Photograph of the fabricated broadband 3 dB 90° hybrid with a vertically installed planar structure.

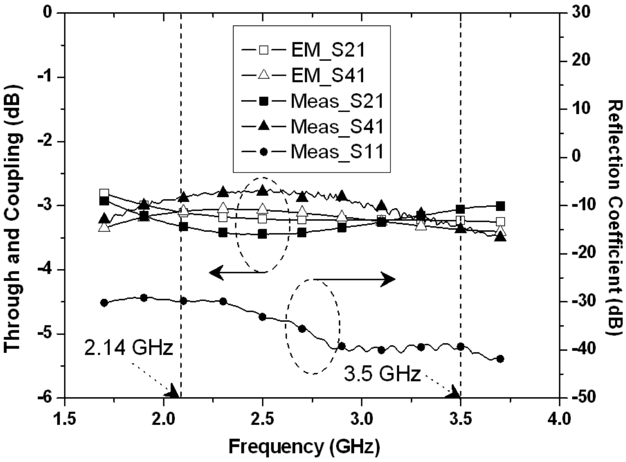


Fig. 7. Comparison of EM simulation and measurement.

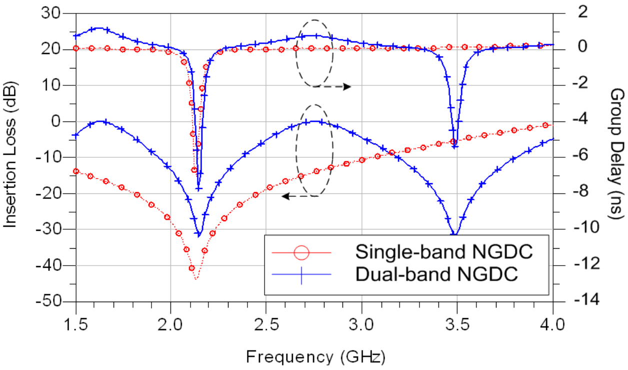
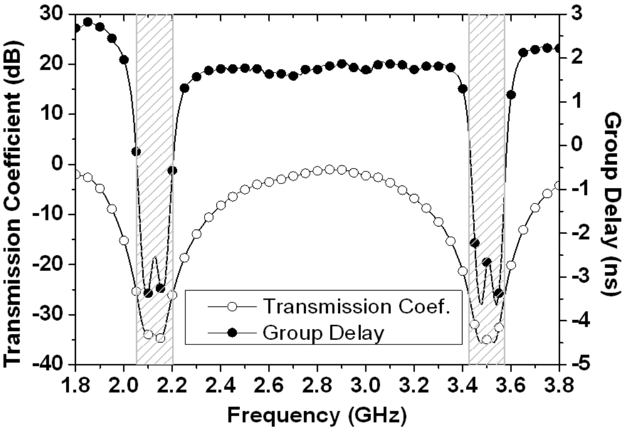
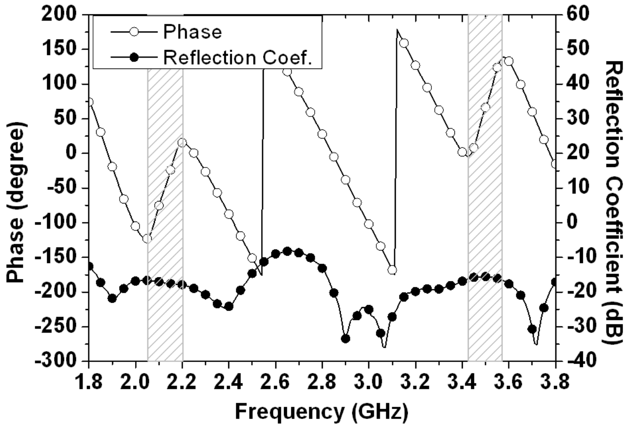


Fig. 8. Simulated group delay and reflection coefficient of the 1-stage single-band [10] and dual-band NGDC.

Fig. 9 shows the measured 2-stage dual-band NGDC. In unit #1, C_{COMP}=0.8 pF, C_L=1.8 pF, 2C_L=3.0 pF, $|\theta_{RH}|$=188°, L_L=35°/133 Ω (short stub) were used in practical realization to obtain the dual-band operation at f_1 and f_3. In unit #2, C_{COMP}=0.9 pF, C_L=1.7 pF, 2C_L=3.4 pF, $|\Theta_{RH}|$=181°, L_L=33°/133 Ω (short stub) were used to obtain the dual-band operation at f_2 and f_4. For both units, an R_{RP} of 47/500 Ω were used. The insertion loss and group delay are shown in Fig. 9(a), and the phase and return loss are presented in Fig. 9(b). The highlighted areas show the NGD regions. The NGD of −3.0



(a) Insertion loss and group delay



(b) Phase and return loss

Fig. 9. The measured results of the 2-stage dual-band NGDC. Phase slopes are inverted in the highlighted dual-band NGD regions.

±0.4 ns and −3.1±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±0.5 dB and −34.9±0.7 dB, respectively. The maximum return loss was −17 dB. When compared to the reference results presented in [14], the 2-stage dual-band NGDC had a wider bandwidth, showing practical applicability. According to the results from [10], a small signal general purpose gain amplifier with small power consumption (<0.5 W) and with small additional group delay (<0.2 ns) can be used to compensate for the insertion loss of around 35 dB. For high power applications over a few tens of watts, this extra power consumption has a slight effect on the total system efficiency.

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 smaller or even zero GD). For example, in case of intermodulation distortion of the cancellation loop in an analog feedforward amplifier, NGDC can be used to eliminate a lossy delay element and increase the system efficiency [12]. Fig. 10 shows the photograph of the fabricated 2-stage dual-band NGDC. The total size is 140×70 mm^2.

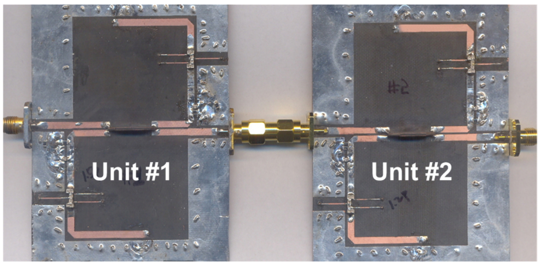


Fig. 10. A photograph of the fabricated 2-stage dual-band NGDC.

Ⅳ. Conclusion

In this paper, we propose the novel design and implementation of a 2-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 given its ability to reduce lossy output delay elements and improve the efficiency of the systems through the dual-band positive phase response characteristics.

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