2.14/3.5 GHz novel dual-band negative group delay circuit design based on composite right/left handed transmission line

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Abstract— **This paper proposes a novel design and implementation of a dual-band negative group delay circuit (NGDC) using composite right/left handed (CRLH) transmission line. CRLH λ/4 short stubs and a broadband 3dB 90° hybrid coupler are employed to obtain simultaneously the negative group delay (NGD) condition at two separate bands. The proposed design methodology was used to design a dual-band negative group delay circuit for the frequency bands at 2.14 and 3.5 GHz. Measured group delays were about -7.2 and -6.5 ns at two operational frequencies.**

I. INTRODUCTION

To provide multimedia services including video, music, photo, and other real-time location based services (LBS) in addition to the traditional voice and text message, a service provider inevitably has to utilize more than one frequency band to increase the data rate and the mobility of a user. In this sense, increasing number of researchers is getting involved in the design of devices that are capable of multiple frequencies or multiple modes of operation, whether in the mobile or base-station application [1]-[2].

Recently, some interesting research has led to the experimental validation, and electronic circuit approach of the NGD concept has been researched. The NGD concept is quite intriguing in that typical materials under normal condition do not usually behave in a manner consistent with the theory. In a specific and narrow frequency band of signal attenuation or an anomalous dispersion, the group velocity is observed to be greater than that of c, the speed of light in vacuum, or even be negative. This phenomenon was defined as the superluminal group velocity, and experimental validation with the theoretical analysis about the phenomenon have been presented in the previously reported literature [3]-[5]. In the early stage, the NGD concept has little use in the RF circuit design because of its narrow bandwidth and poor input/output return loss. Some researchers have been investigating on the topology of the NGD and found some useful application in the radio frequency (RF) circuit design [6]-[9]. General synthesis equations and the planar circuit implementation technique have been proposed in [10].

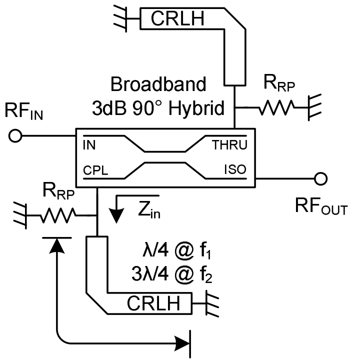

Fig. 1. Proposed dual-band negative group delay circuit.

In this paper, a novel topology of dual-band NGDC using the CRLH transmission line is proposed. The CRLH λ/4 short stubs and a broadband 3dB 90° hybrid coupler are employed to satisfy simultaneously the negative group delay condition at two separate bands. The detail design procedure is described in the following section.

II. DESIGN OF DUAL-BAND NEGATIVE GROUP DELAY CIRCUIT

In a medium of refractive index $n(\omega)$, the dispersion relation can be written

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

Where κ is the wave number. The group velocity (v_g) which means 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 with regard to the frequency, the group velocity can become negative. And this event does happen near an absorption line or signal attenuation condition, where "anomalous" wave propagation effects can occur [5]. Typically, in RF circuit design which is based on the dielectric laminate, we cannot control the refractive index of the given material. Therefore, we are only able to obtain the negative group delay through the resistive signal attenuation, of which the gain is shown to be easily compensated with the small signal gain amplifier without reducing the amount of negative group delay.

Fig. 1 illustrates the topology of the proposed dual-band NGDC. The proposed circuit consists of the broadband 3dB 90° hybrid coupler and the termination resistor R_{RP} together with the CRLH λ/4 short stubs. In this paper, the centre frequencies of the two bands of interest are separated over 1 GHz. So the broadband and 3dB hybrid coupler is required. If the two desired bands are close enough from each other, the broadband 3dB 90° hybrid can be replaced with the single band 3dB coupler.

The NGD in case of a reflective parallel (RP) type passive RF circuit can be obtained according to the following equation

$$\tau = -\left.\frac{d\phi_{\text{in}}}{d\omega}\right|_{\omega=\omega_1,\omega_2} = \frac{4R_{RP}^2 C_{RP} Z_0}{R_{RP}^2 - Z_0^2}, \qquad (3)$$

Where Φ_{in} is the phase of the input impedance of Z_{in} as shown in Fig. 1, Z_0 is the termination impedance of the 90° hybrid coupler which is typically 50 Ω, and ω_1 and ω_2 are the resonant frequencies of the stubs [10]. A group delay (GD), τ, is a function of C_{RP} and R_{RP}, and mainly dependent on R_{RP}. In Fig. 1, the coupling and through port of the 90° hybrid circuit are terminated with R_{RP} at the resonant frequency, which implies the input impedance of the λ/4 stub should be open at the desired frequencies. This can be easily achieved by adapting the CRLH transmission line.

The CRLH transmission line, which is a combination of the conventional right-handed (RH) and the left-handed (LH) transmission line as shown in Fig. 2, exhibits a band-pass magnitude response, and its phase response shows much more interesting characteristics. Fig. 2 shows the dual-band λ/4 short stub employed in the proposed topology. Due to the positive phase response of the LH component, the CRLH transmission line demonstrates higher phase slope then RH line for a fixed electrical length.

In other words, the electrical length of odd multiple of -90° (wavelength of λ/4 and 3λ/4) are obtainable at the odd harmonic frequencies in case of RH line, which is illustrated as the trace with the triangle marker in Fig. 3. However, the frequency with the wavelength of 3λ/4, which means the second desired frequency, can be controlled by adjusting the number of stages of LH unit cell (N) and the lumped element values (C_L, L_L) together with the electrical length of RH lines ($\theta_{RH}=\theta_1+\theta_2$) within the condition of $1<f_2/f_1<3$. Using the design equation presented in [11], we have simulated the circuit shown in Fig. 2 when f_1 and f_2 were 2.14 and 3.5 GHz and the results are presented in Fig. 3.

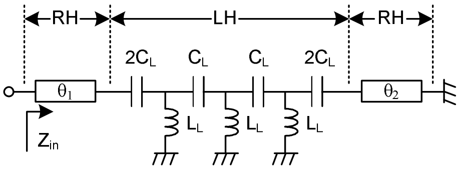

Fig. 2. Detailed circuit of CRLH line employed in this work in case of N=3.

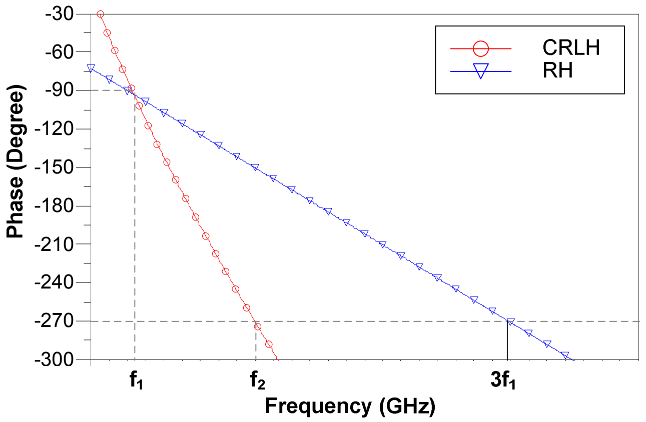

Fig. 3. Simulated phase response of CRLH dual-band λ/4 and RH λ/4 transmission line.

TABLE I
COMPONENT VALUES FOR CRLH LINE SIMULATION

N=3	Calculation	EM Simulation	Measurement
C_L (pF)	2.1321	1.8	1.5
$2C_L$ (pF)	4.2642	3.0	3.0
L_L (nH)	5.3302	Short stub 36°, 133Ω @ f_1	Short stub 36°, 133Ω @ f_1
$\theta_{LH@f1}$ (deg)	119.9155	-	-
$\theta_{RH@f1}$ (deg)	-209.9155	-183.5290	-183.5290

Component values required for the simulation are summarized in Table I, including the calculated values using the design equation, the optimized values through the EM simulation, and the values used for measurement. Due to the limited feasibility of the lumped inductors, they were implemented with the equivalent high impedance short stubs. And the electrical length and the characteristic impedance of the high impedance short stubs are 30° and 130Ω, respectively.

Circuit level simulation result of the proposed dual-band NGDC is shown in Fig. 4 by integrating the optimized CRLH λ/4 short stubs and the ideal broadband 3dB 90° hybrid coupler when R_{RP}=47.6 Ω. Referring to the simulation, the obtained NGD at 2.14 GHz and 3.5 GHz are -7.7 ns and -5.4 ns, respectively. Signal attenuations at two bands are around 30 dB, which can be easily compensated with the 2-stage small signal gain amplifier as ERA-5SM of Mini-Circuits, for example. And the GD of the small signal gain amplifier can be ignored since it is much smaller than the negative GD of the NGDC.

III. EXPERIMENTAL RESULTS

The broadband 3dB 90° hybrid coupler has been employed as a hybrid coupler to cover 2.14 GHz and 3.5 GHz at the same time. Due to the extremely narrow coupling gap in the central coupling element, caused by too small odd impedance, a design of 3dB planar multi-section coupler with broad bandwidth is physically a tough goal. Based on the design method proposed in [12], the broadband 3dB 90° hybrid coupler which covers f_1=2.14 GHz and f_2=3.5 GHz has been designed using the vertically installed planar (VIP) structure to increase the coupling area at the central coupling element.

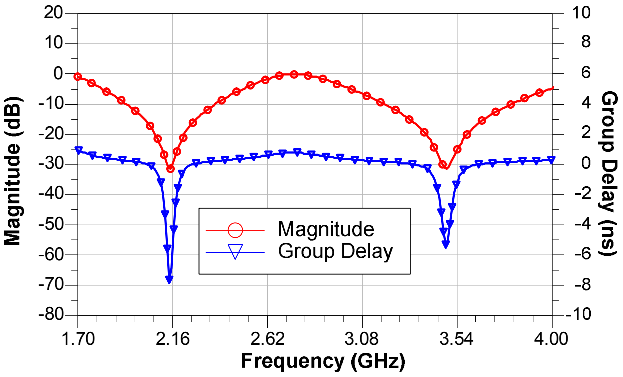

Fig. 4. Circuit simulation results of the proposed circuit.

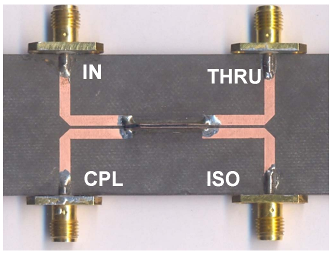

Fig. 5. Photograph of the fabricated broadband 3dB 90° hybrid with the vertically installed planar structure.

Fig. 5 shows the photograph of the fabricated broadband 3dB 90° hybrid coupler, and the measured result compared with the EM simulation are shown in Fig. 6. 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 3dB 90° hybrid coupler is designed and implemented according to the proposed design method, and fabricated with a microstrip line.

Fig. 7 shows the measured results of the complete dual-band NGDC, and the photograph of the fabricated circuit is shown in Fig. 8. The magnitude and group delay response are shown in Fig. 7 (a) and the magnitude and phase response are shown in Fig. 7 (b). In the designed NGD region where the center frequencies are 2.14 and 3.5 GHz, the observed insertion losses were around 30 dB and the negative group delay is observed to be -7.2 ns and -6.5 ns, respectively. The measurement results agree pretty well with the simulation.

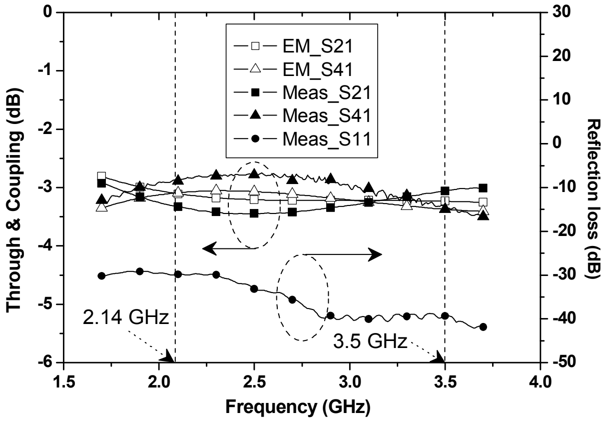

Fig. 6. Comparison results of full 3D electro-magnetic simulation and measurement.

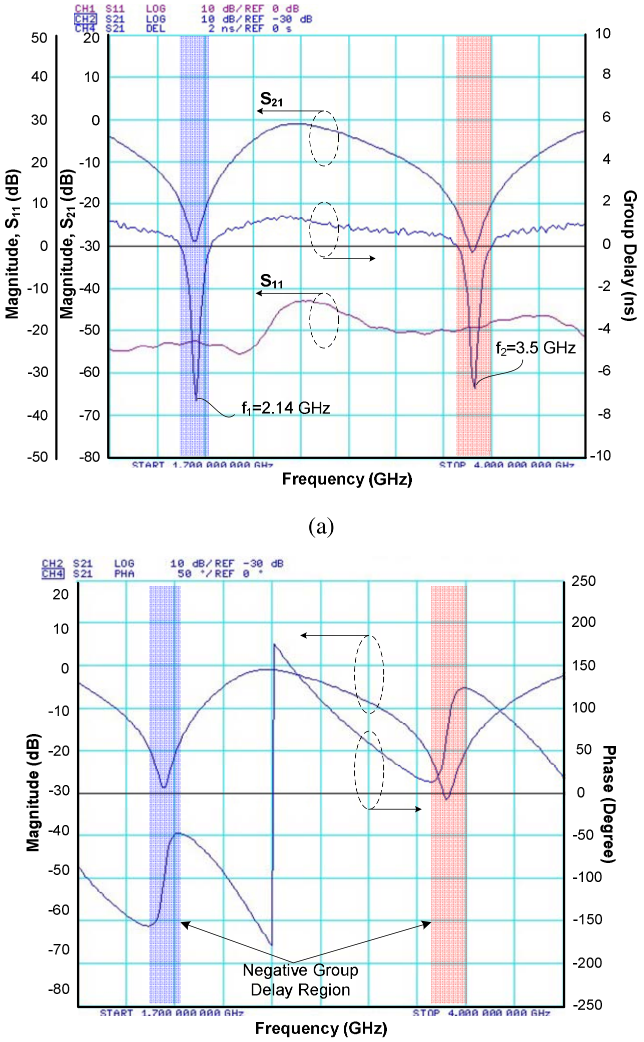

Fig. 7. Measured results: (a) insertion loss, return loss, and group delay response and (b) insertion loss and phase response. The slopes of the phase are inverted in the dual-band negative group delay regions which are highlighted with blue and red box.

The desired values for the termination resistor R_{RP} are obtained by the parallel combination of two chip resistors. However small it may be, the parasitic reactance component of a chip resistor may add up to contribute to the discrepancy between the simulation and measurement. Therefore the size of the chip resistor should be as small as possible. The end of the stub is connected to the ground through a metallic via.

In the NGD region, the slope of the phase is observed to be positive, implying that the group velocity is negative. The negative group velocity can be translated as 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 the conventional circuit, consequently achieving zero phase slope (therefore smaller or even zero GD). The total size of fabricated dual-band NGDC is 70×70 mm^2.

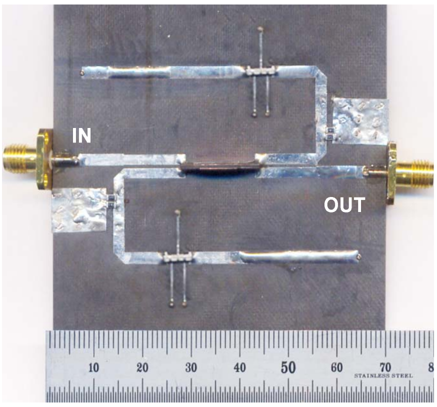

Fig. 8. Photograph of the fabricated dual-band NGDC.

IV. CONCLUSIONS

In this paper, we propose the novel design and implementation of dual-band negative group delay circuit using composite right/left handed transmission line. The composite right/left handed λ/4 short stubs and broadband 3dB 90° hybrid coupler are employed to obtain simultaneously the negative group delay condition at two separate bands. The importance of the proposed work lies in the dual-band design for the interesting property of negative group delay, which can be translated into the opposite direction of the envelope propagation or can be termed time advancement. Because the proposed dual-band NGDC has a limited bandwidth at each band of interest, we are going to extend bandwidth to be applicable to WCDMA and WiMAX applications.

V. ACKNOWLEDGMENT

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