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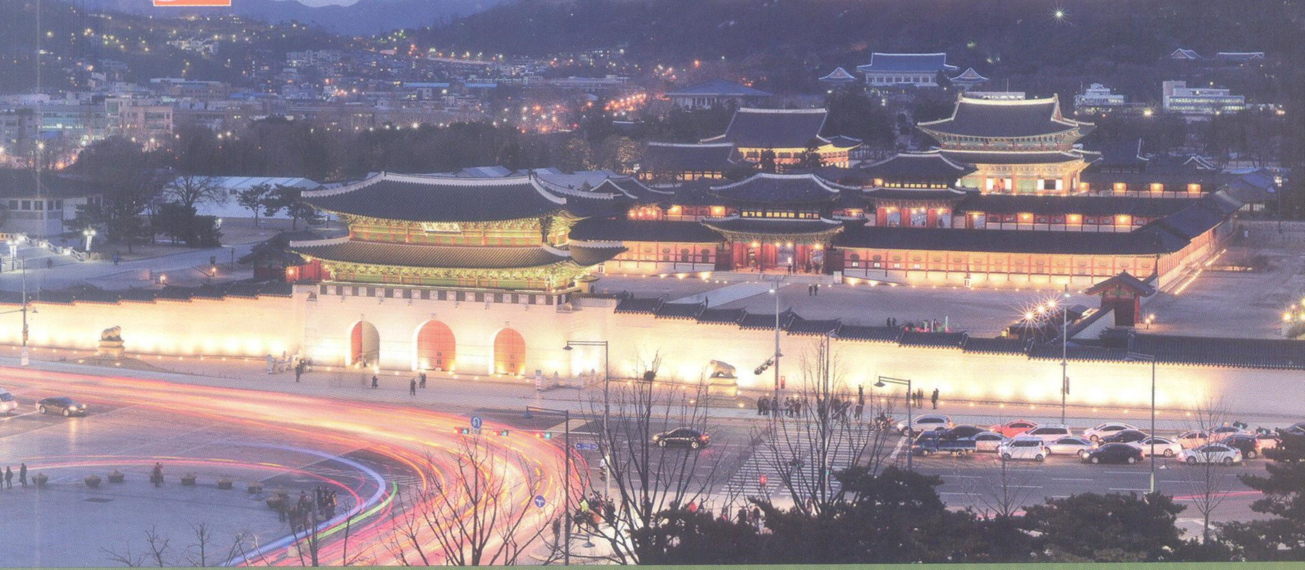
The 16th International Symposium on Microwave and Optical Technology

ISMOT 2017



Program/Abstract Book

June 26-28, 2017

Kbiz Conference Hall, Seoul, Korea

KIEES Korean Institute of Electromagnetic Engineering and Science

TB3-2 160084
(13:55 - 14:15)

Array Diagnosis of Conformal Arrays From Near-field Measurements Using Sparse Bayesian Learning
**Mr. Binzheng Long, Ying Zhang and Hua Peng (University of Electronic Science and Technology,Chengdu,China, China)*

TB3-3 160039
(14:15 - 14:35)

A 3D Printed Frequency Independent Lens for Integrated Lens Antennas
*Mr. Eon-Seok Jo and *Dongho Kim (Sejong University, Korea)*

TC1 - Communication Technologies 3

Tuesday, June 27, 15:15~16:35, Large Conference Hall 2

Chair: Prof. Banmali Rawat (Univ. of Nevada)

TC1-1 160015
(15:15 - 15:55)

[Invited] Simulation of Optimal Power Coupling in a Carrier Wave Reutilized Digital Link Using DBPSK and ASK Modulation
**Mathew H. Henderson and Dr. Banmali S. Rawat (University of Nevada, Reno, United States)*

TC1-2 160130
(15:55 - 16:35)

[Invited] Multimodal mmWave antennas for 5G networks & Invisible antennas using mesoscale conductive polymer wires embedded within OLED displays
**Prof. Wonbin Hong (POSTECH (Pohang University of Science and Technology), Korea)*

TC2 - Passive Components 2

Tuesday, June 27, 15:15~16:35, Medium Conference Room

Chair: Prof. HongJoon Kim (Kyungpook Nat.'l Univ.)

TC2-1 160018
(15:15 - 15:35)

[Invited] Bandwidth Enhancement of Negative Group Delay Circuit Using Finite Unloaded Quality Factor Resonators
*Dr. Girdhari Chaudhary, Boram An, Phirun Kim and *Yongchae Jeong (Chonbuk National University, Korea)*

TC2-2 160050
(15:35 - 15:55)

Optimization of Vertical Transition Utilizing Patterned Grooves on Ground Plane for Frequencies up to 50 GHz
*Mr. Junho Park, Dooseok Choi and *Wonbin Hong (POSTECH, Korea)*

TC2-3 160097
(15:55 - 16:15)

Thin-Film-Based Coplanar Waveguide Resonator with Series Stubs
*Dr. Hyun-Wook Lee, Jae-Hyun Choi and Kyung-Hak Lee (Center for Integrated Smart Sensors, Korea), *Jong-Chul Lee (Kwangwoon University, Korea)*

TC2-4 160051
(16:15 - 16:35)

28 GHz Via-Less Patch Antenna featuring Partially Metallized Side Walls
*Mr. Seung Yoon Lee, Dooseok Choi and *Wonbin Hong (POSTECH, Korea)*

TC3 - Analysis Method 3

Tuesday, June 27, 15:15~16:55, Small Conference Room 1

Chair: Prof. Jun Shibayama (Hosei Univ)

Bandwidth Enhancement of Negative Group Delay Circuit Using Finite Unloaded Quality Factor Resonators

Girdhari Chaudhary[1], Boram An, Phirun Kim and Yongchae Jeong*

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***Abstract* - This paper presents a design of negative group delay (NGD) circuit with enhanced bandwidth using the finite unloaded quality factor (Q_u) resonators at microwave frequency. Unlike the conventional NGD topologies, the proposed NGD circuit does not require any external resistor to generate NGD. The proposed circuit is synthesized using coupling matrix with finite Q_u. Analytical design expressions are provided to obtain predefined NGD with matched input/output ports. To enhance the NGD bandwidth, the NGD circuits with slightly different center frequencies are cascaded. The measurement results are in good agreement with the simulations and predicated theoretical results.**

***Index Terms* - Abnormal negative group delay velocities, coupling matrix, finite unloaded quality factor resonators, negative group delay circuit.**

I. INTRODUCTION

Frequency-dependent group delay (GD) is inversely proportional to group velocity and can be examined by the phase (φ) variation of a forward transmitting scattering parameter. Mathematically, the GD is defined by the differential-phase relation as (1).

$$\tau_g = -\frac{d\varphi}{d\omega}. \tag{1}$$

Using (1), the presence of negative group delay (NGD) in a medium is equivalent to increasing a phase (positive slope) with a frequency. Therefore, the NGD refers to the phenomenon whereby an electromagnetic wave traverses a dispersive material or electronic circuit in such a manner that its amplitude envelope is advanced through media rather than undergoing delay [1]. However, this phenomenon does not violate a causality, since the initial transient of the pulse is still limited to the front velocity that does not exceed the speed of light in a vacuum [2]. The effect of NGD is observed within a limited frequency band when the absorption or attenuation is at a maximum.

The NGD circuits have applied in various practical applications in communication systems, such as shortening or reducing delay lines, enhancing the efficiency of feedforward linear amplifiers, designing broadband and constant phase shifters, the realization of non-Foster reactive elements, and minimizing beam-squint in series-fed antenna arrays [3]-[5].

In a microwave regime, the NGD circuits have been designed using lumped elements and distributed transmission line resonators along with the resistor (R) because the NGD cannot be exhibited without R [3]-[9]. Moreover, the conventional NGD circuits suffer from high signal attenuation (SA), smaller NGD bandwidth, and worse magnitude (S_{21}) flatness. While a few works have been performed for reducing SA [6]-[8], these works still suffer from small NGD bandwidth and the magnitude flatness problem. To overcome these problems, researchers have attempted to design NGD circuits using different methods such as cross-coupling between resonators [8], increasing the number of resonators [10] and transversal-filter topologies [11]. On the other hand, these works showed very high SA (> 28 dB for -1 ns). Moreover, except for the work of [11], these NGD circuits also used R for generating NGD, which prevents fully distributed circuit realization.

This paper presents the design of a fully distributed NGD circuit with predefined NGD, good magnitude flatness, and wide NGD bandwidth. The design method is based on a coupling matrix along with finite unloaded-quality factor (Q_u) resonators. This proposed topology does not require any R for generating NGD, or any extra network for matching input/output ports with reference termination impedances. Therefore, the proposed work allows fully distributed transmission line circuit realization.

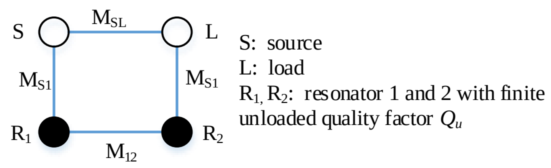

Fig. 1. Coupling diagram of the proposed negative group delay circuit.

II. DESIGN EQUATIONS

Fig. 1 shows the coupling diagram for the proposed NGD circuit where both external couplings (M_{S1} and M_{L2}) are equal. Similarly, the resonator self-coupling values, the source-to-load (M_{SL}) coupling, and the load-to-source coupling (M_{LS}) have the same magnitude. With a finite Q_u of resonators, the $(N + 2) \times (N + 2)$ coupling matrix of the generalized second-order filter [12] corresponding to the coupling diagram shown in Fig. 1 is given as (2).

$$M = \begin{bmatrix} 0 & M_{S1} & 0 & M_{SL} \\ M_{S1} & -\dfrac{j}{Q_u\Delta} & M_{12} & 0 \\ 0 & M_{12} & -\dfrac{j}{Q_u\Delta} & M_{S1} \\ M_{SL} & 0 & M_{S1} & 0 \end{bmatrix}, \qquad (2)$$

where the subscripts S, L, 1, 2, and Δ correspond to the source, load, the first resonator, the second resonator, and 3-dB fractional bandwidth, respectively.

Furthermore, the reflection (S_{11}) and transmission (S_{21}) responses corresponding to the coupling relationship (2) are given as (3), where $\Omega = 1/\Delta(\omega/\omega_0 - \omega_0/\omega)$ is the normalized frequency in rad/s [13].

$$S_{11} = 1 - \frac{\Omega^2 - \dfrac{1}{Q_u^2\Delta^2} - \dfrac{2j\Omega}{Q_u\Delta} - \dfrac{M_{S1}^2}{Q_u\Delta} - M_{12}^2 - jM_{S1}^2\Omega}{\left\{\begin{aligned} & 0.5\left(M_{SL}^2 + 1\right)\left\{\begin{aligned} &\Omega^2 - \frac{1}{Q_u^2\Delta^2} \\ &-M_{12}^2 \end{aligned}\right\} - \frac{j}{Q_u\Delta}\left(\begin{aligned} &\Omega + M_{SL}^2\Omega \\ &-jM_{S1}^2 \end{aligned}\right) \\ & +M_{12}M_{S1}^2M_{SL} - 0.5M_{S1}^4 - jM_{S1}^2\Omega \end{aligned}\right\}} \qquad (3a)$$

$$S_{21} = \frac{2\left\{M_{SL}\Omega^2 - \dfrac{M_{SL}}{Q_u^2\Delta^2} - M_{SL}M_{12}^2 + M_{12}M_{S1}^2 - \dfrac{2jM_{SL}\Omega}{Q_u\Delta}\right\}}{\left\{\begin{aligned} & 2M_{S1}^2\Omega + \frac{2M_{SL}^2\Omega}{Q_u\Delta} + \frac{2\Omega}{Q_u\Delta} + j\left(M_{SL}^2 + 1\right)\left(\begin{aligned} &\Omega^2 - M_{12}^2 \\ &-\frac{1}{Q_u^2\Delta^2} \end{aligned}\right) \\ & +j\left(2M_{12}M_{S1}^2M_{SL} - M_{S1}^4 - \frac{2M_{S1}^2}{Q_u\Delta}\right) \end{aligned}\right\}} \qquad (3b)$$

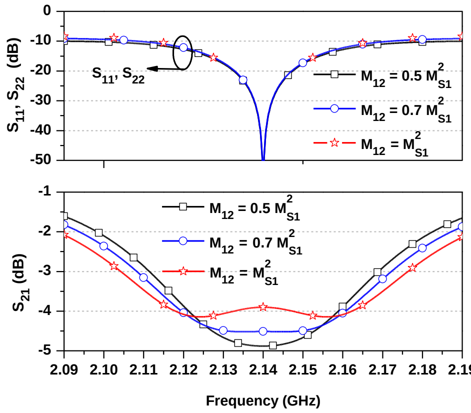

Fig. 2. Calculated S-parameters of negative group delay circuit.

where ω and ω_0 are the operating and center angular frequencies of the NGD circuit. For the matched input/output ports, S_{11} in (3a) is set to zero at $\omega = \omega_0$ to find the relationship between M_{SL} and M_{S1} with the assuming $M_{12} = aM_{S1}^2$, where a is any real positive value. For an arbitrary value of M_{S1}, the relationship between M_{SL} and M_{S1} for the matched input/output ports at $\omega = \omega_0$ can be found with (4).

$$M_{SL} = \frac{aM_{S1}^4 \mp \sqrt{a^2M_{S1}^8 + \left(a^2M_{S1}^4 + \dfrac{1}{Q_u^2\Delta^2}\right)\left\{\begin{aligned} &M_{S1}^4\left(a^2 - 1\right) \\ &+\frac{1}{Q_u^2\Delta^2} \end{aligned}\right\}}}{a^2M_{S1}^4 + \dfrac{1}{Q_u^2\Delta^2}} \qquad (4)$$

Furthermore, using (3b), the GD of the proposed NGD circuit can be calculated as (5), where M_{SL} can be obtained from (4) for the matched input/output conditions at center frequency f_0.

$$\tau_g = -\frac{\omega^2 + \omega_0^2}{\omega_0\omega^2\Delta}\frac{d\angle S_{21}}{d\Omega} \qquad (5)$$

To illustrate the above design equations, the calculated responses of the proposed NGD circuit are shown in Figs. 2 and 3 for different values of the coupling matrix. As observed from Fig. 2, the input/output ports are matched at ω_0. Similarly, from Fig. 3, S_{21} is increased as M_{12} increases toward a higher value. Moreover, the maximum GD at ω_0 and the NGD bandwidth (which is defined as bandwidth when GD < 0) are also increased when M_{12} is changed as shown in Fig. 3 implying the need for controlling the coupling between resonators 1 and 2. Therefore, a strong coupling is required for a wider NGD bandwidth. However, this decreases the maximum NGD at ω_0.

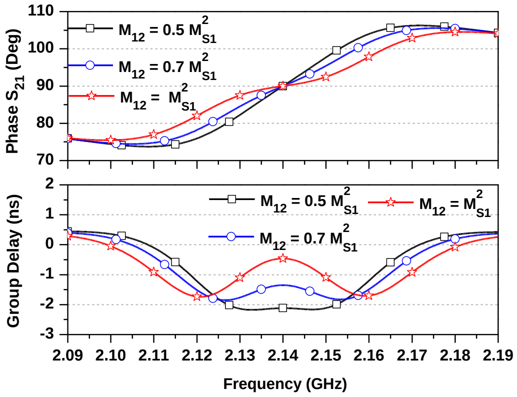

Fig. 3. Calculate phase/group delay responses of negative group delay circuit with M_{S1} = 0.74, Q_u = 50 and Δ = 2%.

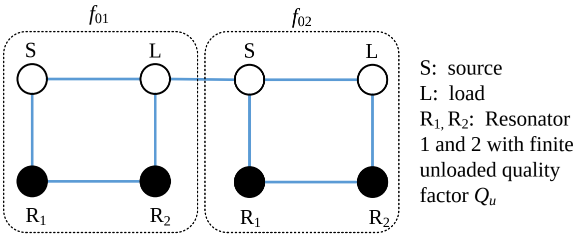

Fig. 4. Coupling diagram of the cascaded 2-stage negative group delay circuit for bandwidth enhancement.

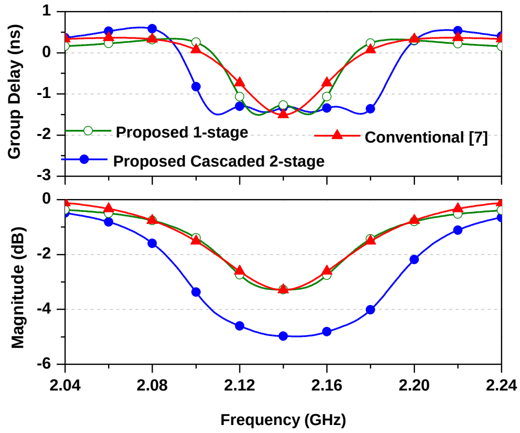

Fig. 5. Calculated group delay/magnitude responses of negative group delay circuits.

Fig. 4 shows the coupling diagram of the proposed NGD circuit for bandwidth enhancement, where two NGD circuits with slightly different center frequencies are cascaded. Fig. 5 shows the calculated GD/magnitude responses of cascaded circuit. As seen from this figure, the proposed cascaded NGD circuit with slightly different center frequencies provides wider NGD bandwidth as compared with 1-stage and conventional NGD circuits. However, the SA is slightly higher than 1-stage and conventional NGD circuits. Therefore, trade-off exists between NGD bandwidth and SA.

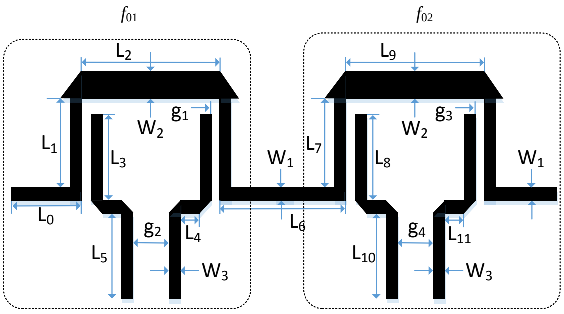

Fig. 6. EM simulation layout of fabricated negative group delay circuit. Physical dimensions: L_0 = 6.8, L_1 = 12.3, L_2 = 17.4, L_3 = 13.8, L_4 = 1.5, L_5 = 19.9, L_6 = 18.6, L_7 = 12.1, L_8 = 12.8, L_9 = 17.2, L_{10} = 18.2, L_{11} = 1.4, W_1 = 1.8, W_2 = 3.8, W_3 = 1.8, g_1 = 0.6, and g_2 =6. (Unit: mm).

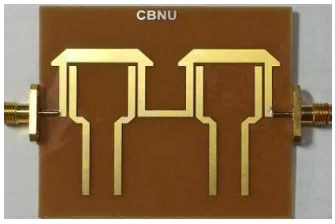

Fig. 7. Photograph of fabricated circuit.

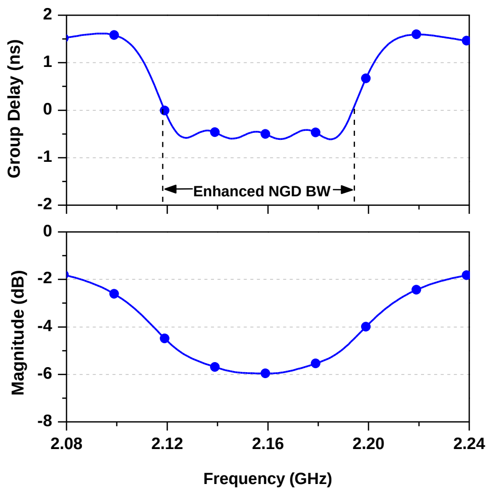

Fig. 8. Measured group delay/magnitude results of the fabricated circuit.

III. SIMULATION AND MEASUREMENT RESULTS

To experimental demonstration, the NGD circuit with GD of -0.5 ns was designed and fabricated at f_0 = 2.16 GHz on an FR-4 epoxy substrate with a dielectric constant (ε_r) of 4.4, thickness (h) of 0.787 mm, and loss tangent of 0.02. For enhanced NGD bandwidth, two NGD circuits were designed at f_{01} = 2.125 GHz and f_{02} = 2.18 GHz, respectively and cascaded. The coupling matrix of NGD circuits is given as M_{S1} = 1.01, M_{12} = 1.3261, M_{SL} = 1.3307 with Q_u = 40 and Δ = 2%.

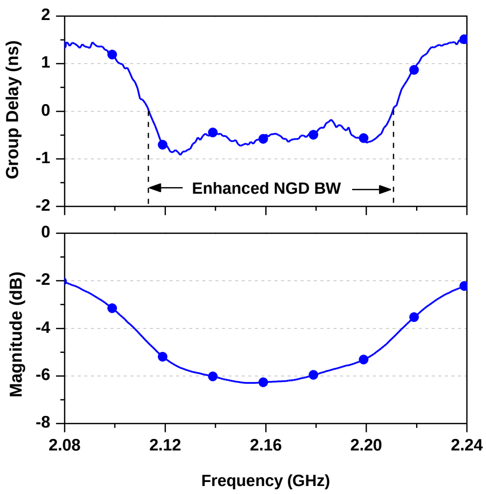

Fig. 9. Measured group delay/magnitude results of the fabricated circuit.

The resonators were implemented with an open-circuited $\lambda/2$ transmission line. Similarly, coupling between the source and load is implemented with a step-impedance $3\lambda/4$ line. The EM layout and photograph of the fabricated circuit are shown in Figs. 6 and Fig. 7.

Fig. 8 shows the simulated GD/magnitude results of enhanced NGD bandwidth circuit. The simulated GD and magnitude at f_0 = 2.16 GHz are given as -0.516 ± 0.06 ns and -5.964 dB, respectively. Similarly, the measured results of fabricated circuit are shown in Fig. 9. From the experiment, the values of magnitude and GD at f_0 = 2.16 GHz are determined as -6.25 dB and -0.583 ± 0.08 ns, respectively. The NGD bandwidth is determined as 100 MHz, providing NGD-bandwidth product of 0.0583. The input/output return losses at f_0 = 2.16 GHz are greater than 15 dB.

IV. CONCLUSION

In this paper, we investigated a comprehensive method to design a negative group delay circuit with enhanced bandwidth and magnitude flatness based on a coupling matrix along with finite unloaded-quality factor of resonators. Analytical design equations are provided to calculate the coupling matrix with the predefined negative group delay. The advantage of the proposed circuit topology is that circuits do not need any additional lumped elements and therefore are very suitable for high frequency, in which lumped elements are not obtainable. The design theory is validated by fabricating a circuit at the center frequency of 2.16 GHz. The proposed circuit can be applied in various applications such as the realization of a non-Foster reactive element and series-fed antenna arrays for minimizing the beam-squint problem.

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