A Low-Loss Dual-Band Negative Group Delay Circuit with Flexible Design

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Abstract—A low-loss dual-band negative group delay circuit (NGDC) with a flexible design is proposed. The proposed NGDC consists of a transmission line coupled asymmetrically with two step-impedance open-loop resonators. The negative group delay (NGD) times and center frequencies of the lower and upper bands can be tuned independently. To verify the design concept, two dual-band NGDC prototypes I and II are fabricated and measured. The measured NGD times of prototype I are \(-4.9\) ns and \(-4.8\) ns at the center frequencies of 1.949 GHz and 2.054 GHz, respectively. The insertion loss is lower than 2.7 dB and the return loss larger than 11.2 dB in both NGD bands. For prototype II, the NGD times at 1.949 GHz and 2.086 GHz are \(-4.7\) ns and \(-3.3\) ns, respectively. The measured insertion loss is better than 2.4 dB with the return loss larger than 11.9 dB.

1. INTRODUCTION

The distortion of group delay (GD) is one of the challenging issues in a circuit or system, which may distort the signal by introducing inter-symbol interference. Therefore, the GD equalization technique based on the negative group delay circuit (NGDC) arises at the historic moment [1–3]. The traditional NGDCs are usually realized by RLC resonators [4] or transmission line resonators loaded with resistors [5, 6]. Recently, some novel structures have been implemented, such as miniaturization [7], flatness of GD [8], and reconfigurable [9]. However, these NGDCs always suffer from high signal attenuation. So the research on low-loss NGDC has attracted more and more attention [10–13]. Based on lossy transmission lines, signal attenuation can be reduced.

With the rapid development of various wireless systems for multiple-access and multifunctional applications, multiband microwave components that can simultaneously support different communication standards are essential. To satisfy the GD compensation for multiband devices, it is important to increase the number of operation bands of NGDCs. Over the last decade, several dual-band NGDCs have been designed [14–20]. In [14], a dual-band NGDC based on right/left-handed \(\lambda/4\) shorted stubs is proposed. However, this circuit works as a reflection-type that necessarily demands a broadband hybrid coupler to realize port-matching. In [15], a two-stage FET-based active circuit is used to produce dual-band negative group delay (NGD). However, the analysis and design of the active circuit are complicated. Therefore, distributed-parameter NGDCs are proposed. In [16, 17], the frequency ratio of the lower and upper bands is controlled by the characteristic impedance of the transmission lines. However, these two NGD center frequencies \(f_1\) and \(f_2\) depend on the center frequency \(f_0 = (f_1 + f_2)/2\). To achieve independent controllability, the defected structures are adopted in [18]. The center frequencies of the lower and upper bands can be individually adjusted by a defected microstrip structure and a defected ground structure, while the NGD time can be tuned by changing the loaded resistances. Another dual-band NGDC consists of a couple of open-circuited stubs, whose frequencies of the lower and upper bands are controlled by the length of stubs [19]. However, port matching cannot be

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achieved. In [16–19], the insertion loss (IL) is large. To reduce signal attenuation, a dual-band NGDC with three lossy transmission lines and two identical coupled lines is proposed in [20]. However, its two NGD bands cannot be designed separately.

In this paper, a low-loss dual-band NGDC with a flexible design of both NGD bands is proposed. The proposed NGDC is composed of a couple of step-impedance open-loop resonators and a transmission line connecting input/output ports. By asymmetrically coupling the resonators with the transmission line, the dual-band NGD characteristic is realized. The center frequencies of the lower and upper NGD bands \( f_1 \) and \( f_2 \) can be tuned independently by the characteristic impedance of the step-impedance resonators without depending on the center frequency \( f_0 \). Meanwhile, by tuning the coupling gaps, the individual adjustment of NGD times for both bands can be achieved. The analysis and results of the proposed low-loss dual-band NGDC are given and discussed.

2. DESIGN OF LOW-LOSS DUAL-BAND NGDC

The configuration of the proposed low-loss dual-band NGDC is illustrated in Fig. 1. It consists of two step-impedance open-loop resonators and a transmission line connecting input and output ports. Due to the asymmetrically coupling between the transmission line and the open-loop resonators, the individually-adjusted dual-band NGD characteristic can be realized. The NGD characteristic of the proposed dual-band NGDC is generated by the step-impedance open-loop resonators. Therefore, the NGD time is mainly determined by the width of coupled transmission lines and coupling gaps. The center frequencies of two NGD bands \( f_1 \) and \( f_2 \) can be adjusted by the characteristic impedance of the step-impedance resonators without relying on the center frequency \( f_0 \).

![Figure 1. Configuration of the proposed low-loss dual-band NGDC.](image)

Figures 2 and 3 show the effects of the coupling section on the performances of the proposed dual-band NGDC. As shown in Fig. 2, when \( W_{c1} \) is increased from 0.8 to 2.8 mm, the NGD absolute values and IL at the center frequencies of both NGD bands are increased with a slight change of \( |S_{11}| \) at \( f_1 \) and \( f_2 \). When \( W_{c2} \) is increased from 3.4 to 4.4 mm, both NGD center frequencies are decreased; meanwhile, the NGD absolute values and IL are decreased. As shown in Fig. 3, the gaps of the coupling section \( S_1 \) and \( S_2 \) have independent effects on the upper and lower bands, and the NGD absolute values and IL at \( f_1 \) (\( f_2 \)) are inversely proportional to \( S_2 \) (\( S_1 \)). Therefore, by tuning \( S_1 \) and \( S_2 \), the independent adjustment of NGD time for both bands can be achieved.

Fig. 4 gives the effects of \( W_1 \) and \( W_2 \) (i.e., the characteristic impedance of the step-impedance resonator) on the performances of the proposed dual-band NGDC. When \( W_1 \) is decreased from 3.3 to 2.3 mm, the center frequency of the upper NGD band is increased, and that of the lower NGD band is slightly changed. Contrary to \( W_1 \), the center frequency of the lower NGD band is increased by decreasing \( W_2 \) from 4.8 to 3.8 mm. Thus, \( W_1 \) and \( W_2 \) can be used to adjust the center frequencies of the upper and lower bands, respectively. Fig. 5 shows the effects of \( L_1 \) and \( L_2 \). When \( L_1 \) or \( L_2 \) is decreased,
Figure 2. Effect of $W_{c1}$ and $W_{c2}$ on the performances of the proposed dual-band NGDC. (a) GD. (b) $S$-parameters.

Figure 3. Effect of $S_1$ and $S_2$ on the performances of the proposed dual-band NGDC. (a) GD. (b) $S$-parameters.

both NGD center frequencies are simultaneously increased.

According to the foregoing analysis, the following procedures are suggested to design the proposed low-loss dual-band NGDC.

1) Determine the center frequencies of the lower and upper bands ($f_1$ and $f_2$) and the NGD times at $f_1$ and $f_2$ according to the design requirements. Obtain the values of relative permittivity and thickness of the substrate.

2) Select proper widths $W_{c1}$, $W_{c2}$, $W_1$, and $W_2$ referring to Figs. 2 and 4. And calculate the lengths $L_1$ and $L_2$ to be about $\lambda/4$ and $\lambda/2$ at $f_0 = (f_1 + f_2)/2$, respectively.

3) Choose proper coupling gaps $S_1$ and $S_2$ referring to Fig. 3.

4) Select a proper length $L_3$ for the connecting lines to ensure that there is no coupling between the microstrip lines with the widths of $W_{c2}$ and $W_1$ ($W_2$). And select a proper length $L_4$ to reduce the coupling between the left and right microstrip lines with the width of $W_{c2}$.

5) Change $L_1$, $L_2$, and $W_{c2}$ in a full-wave electromagnetic simulator to eliminate frequency shift
Figure 4. Effect of $W_1$ and $W_2$ on the performances of the proposed dual-band NGDC. (a) GD. (b) $S$-parameters.

Figure 5. Effect of $L_1$ and $L_2$ on the performances of the proposed dual-band NGDC. (a) GD. (b) $S$-parameters.

due to the connecting lines, referring to Figs. 2 and 5.

6) Tune $W_1$ and $W_2$ according to Fig. 4 to obtain the desired frequencies $f_1$ and $f_2$.

7) Adjust $W_{c1}$, $S_1$, and $S_2$ referring to Figs. 2 and 3 to achieve the needed NGD times at $f_1$ and $f_2$.

3. IMPLEMENTATION AND PERFORMANCE

To validate the design concept, two dual-band NGDCs are designed and fabricated on a substrate with relative permittivity $\varepsilon_r = 2.55$ and thickness $h = 1.5$ mm. The HFSS EM software is used to obtain the optimized dimensions. The final dimensions of prototypes I and II are given in Table 1. Photographs of the fabricated prototypes are shown in Fig. 6. The circuit size of the prototypes is 70.6 mm × 46.6 mm (around $0.67\lambda_g \times 0.44\lambda_g$, where $\lambda_g$ is the guided wavelength of 50-Ω transmission line at $f_1$). The fabricated prototypes are measured with an Agilent N5230A network analyzer.
Table 1. Dimensions of the proposed dual-band NGDC prototypes (unit: mm, referring to Fig. 1).

| Prototypes | $W_1$ | $S_1$ | $S_2$ | $W_{c1}$ | $W_2$ | $W_3$ | $W_4$ | $L_0$ | $L_1$ | $L_2$ | $L_3$ | $L_4$ |
|------------|-------|-------|-------|----------|-------|-------|-------|-------|-------|-------|-------|-------|
| I          | 2.88  | 1.65  | 1.8   | 3.9      | 4.1   | 0.5   | 1.0   | 10.0  | 23.3  | 66.8  | 7.8   | 2.0   |
| II         | 2.50  | 2.00  | 1.8   | 3.9      | 4.1   | 0.5   | 1.0   | 10.0  | 23.3  | 66.8  | 7.8   | 2.0   |

Figure 6. The photograph of the fabricated dual-band NGDCs. (a) Prototype I. (b) Prototype II.

Figure 7 shows the simulated and measured results of prototype I. For the lower NGD band, the measured GD and $|S_{21}|$ at $f_1 = 1.949$ GHz are $-4.9$ ns and $-2.6$ dB, respectively. The fractional bandwidth (FBW) for GD less than 0 ns is 0.46% (1.945–1.954 GHz). For the upper NGD band, the measured GD and $|S_{21}|$ at $f_2 = 2.054$ GHz are $-4.8$ ns and $-2.7$ dB, respectively. The NGD fractional bandwidth is 0.54% (2.047–2.058 GHz). The measured return loss (RL) of both NGD bands is better than 11.2 dB (i.e., $|S_{11}| < -11.2$ dB).

Figure 7. Simulated and measured results of the proposed dual-band NGDC prototype I. (a) GD. (b) $S$-parameters.

For demonstrating the flexible design of the proposed dual-band NGDC (i.e., the NGD times and center frequencies of the NGD bands can be tuned independently), prototype II is designed with only change of $W_1$ and $S_1$ (as shown in Table 1) for $f_1 = 1.949$ GHz and $f_2 = 2.086$ GHz. The simulated
and measured GD and $S$-parameters of prototype II are shown in Fig. 8. The measured GD and $|S_{21}|$ at $f_1 = 1.949$ GHz are $-4.7$ ns and $-2.4$ dB, respectively. The FBW of the lower NGD band is 0.46% (1.945–1.954 GHz). The measured RL is better than 11.9 dB in the lower NGD band. For the upper NGD band, the measured GD and $|S_{21}|$ at $f_2 = 2.086$ GHz are $-3.3$ ns and $-1.8$ dB, respectively. The NGD fractional bandwidth is 0.53% (2.081–2.092 GHz). The measured RL is better than 16.6 dB in the upper NGD band.

Table 2. Performance comparison.

| Ref. | $f_i$ (GHz) | NGD (ns) | IL (dB) | RL (dB) | NGD FBW (%) | FOM | Size ($\lambda_g \times \lambda_g$) | Flexible Design |
|------|-------------|----------|--------|--------|-------------|-----|-----------------|----------------|
| [14] | 2.140       | -3.0     | 34.2   | 17.0   | 8.41        | 0.0105 | $1.80 \times 0.09$ | No             |
|      | 3.500       | -3.1     | 34.9   | 17.0   | 5.14        | 0.0100 |                 |                |
| [16] | 0.667       | -1.2     | 18.2   | 24.8   | 34.5        | 0.0338 | $0.27 \times 0.13$ | No             |
|      | 1.377       | -1.2     | 18.2   | 24.7   | 16.5        | 0.0332 |                 |                |
| [17] | 0.496       | -2.9     | 8.30   | 23.3   | 7.66        | 0.0426 | $0.50 \times 0.19$ | No             |
|      | 1.499       | -3.1     | 10.2   | 25.4   | 3.67        | 0.0519 |                 |                |
| [18] | 3.500       | -4.5     | 47.4   | -      | 3.43        | 0.0023 | $0.64 \times 0.36$ | Yes            |
|      | 5.150       | -4.2     | 38.8   | -      | 1.94        | 0.0048 |                 |                |
| [19] | 3.500       | -5.0     | 13.0   | -      | 5.71        | 0.2237 | $0.64 \times 0.60$ | No             |
|      | 5.200       | -5.0     | 19.5   | -      | 5.77        | 0.1589 |                 |                |
| [20] | 2.436       | -4.1     | 2.13   | 12.6   | 0.49        | 0.0381 | $1.47 \times 1.26$ | No             |
|      | 3.022       | -3.8     | 2.86   | 12.4   | 0.43        | 0.0358 |                 |                |
| Prototype I | 1.949   | -4.9     | 2.60   | 11.2   | 0.46        | 0.0327 | $0.67 \times 0.44$ | Yes            |
| Prototype II | 1.949  | -4.7     | 2.40   | 12.2   | 0.46        | 0.0320 |                 |                |
|       | 2.086       | -3.3     | 1.80   | 16.9   | 0.53        | 0.0295 |                 |                |
Table 2 shows the comparison of the proposed NGDC with previous dual-band designs. Compared with [14, 16–20], the proposed circuit has a lower IL with a moderate RL, circuit size, and figure of merit (FOM), where the FOM is defined as

$$\text{FOM} = |\text{NGD}(f_i)| \times \text{BW}_{\text{NGD}} \times |S_{21}(f_i)|$$

Furthermore, the proposed dual-band NGDC has a flexible design of operation frequencies ($f_1$ and $f_2$) and NGD times.

4. CONCLUSIONS

In this paper, a novel low-loss dual-band NGDC has been presented. The proposed circuit is composed of two step-impedance open-loop resonators and a transmission line connecting input/output ports. Two dual-band NGDCs have been designed, fabricated, and measured. The measurement results are consistent with the simulation ones, which verifies the proposed NGDC with a flexible design of the operation frequencies and NGD times. In addition, the proposed NGDC has a lower IL than previous designs [14, 16–20]. So it can be applied in various dual-band microwave circuits and systems.

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