Novel design of a 2.1–2.9 GHz negative capacitance using a passive non-Foster circuit

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Abstract: Non-Foster circuits (NFC), in conjunction with the effect of negative impedance, have been applied to design broadband radio frequencies (RF) due to their wideband impedance matching ability. There are many approaches to designing non-Foster circuits that use transistors with loops inside to obtain negative reactance. Hence, conventional NFC has some problems, including complex connectivity and power consumption. In this paper, we analyse other properties of NFC phase and group delay, and we realize that these properties are related to properties of negative group delay (NGD) networks. Therefore, we proposed a new design of passive non-Foster circuits, that is less complicated and does not require power.

Keywords: negative impedance, negative group delay, negative capacitance, passive non-Foster circuit

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

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1 Introduction

Conventional wideband matching techniques have bandwidth (BW) problems resulting from the Bode–Fano criterion [1]. The Bode–Fano criterion means that, to achieve broadband characteristics, the RF designer must sacrifice other parameters of the circuit including the large size, more loss and low Quality (Q). A reason for this problem was mentioned in our previous paper [2]: the reactance-versus-frequency slope of the negative capacitor is wider than that of the positive inductor in matching with a positive capacitor from 0.8–1.2 GHz. Therefore, when negative impedance is used in the matching network, the wideband could be easily achieved without increasing the size of circuits or loss parameter.

Non-Foster circuits (NFC) was used in the impedance matching of RF circuits design to antennas in many papers. In antennas design, Sussman-Fort [3] used non-Foster impedance matching to achieve the broadband electrically-small antenna, with a frequency is between 20–120 MHz. In power amplifier design, Sangho Lee [4] used NFC on interstage matching networks to increase the BW from 6–18 GHz. All of the literature describes that conventional NFC consumes power and is difficult to connect due to its pair of transistors and the loop between them required to operate the NFC.

Some properties of NFC could be linked to the reactance of circuit, that phase and group delay. Based on the relation between properties of negative elements and negative group delay (NGD), shown in the Fig. 1, Hassan Mirzaei [5] analyzed and designed a new high Q NFC without using a loop inside the circuit. However, NGD, in his design, suffers much loss parameter; even when using an effective gain amplifier.

![Fig. 1. Phase and group delay of both 5 pF and −5 pF.](image-url)

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In the above figure, when the negative capacitor is employed to match the positive capacitor, the transmission phase of circuit is $0^\circ$; therefore, the circuit is in phase. This benefit of NFC was applied to squint-free broadband leaky-wave antennas [6]. The group delay of the circuit is linked to phase delay and reactance as the following equations:

$$\varphi_{21} = -\tan^{-1} \left( \frac{X_{NF}}{2Z_0 + R_{NF}} \right) \Rightarrow \tau_D = -\frac{\partial \varphi_{21}}{\partial \omega} ,$$

where $\varphi_{21}$ is the transmission phase of NFC and $X_{NF}$ and $R_{NF}$ are the reactance and resistance of the NFC, respectively. $Z_0$, $\tau_D$, and $\omega$ are the characteristic impedance, group delay, and angular frequency of the circuit, respectively. For the ideal negative elements, the NGD is equivalent to an increasing phase with the frequency shown in Fig. 1. Furthermore, the resistance of an ideal negative element is $0 \, \Omega$ so that the ideal negative elements have high $Q$, low loss parameter and pure phases compare with NFC or loss-compensated NGD designed to act like negative elements in certain frequencies using one or many transistors to reduce the effect of resistance of the NFC. Finally, we propose a new NFC design that only uses NGD networks to avoid the power consumption that comes with conventional NFC. However, our design still has loss since it only uses passive components; however, we reduce this loss using small-size lump components and by reducing the size of circuit.

2 Designing a passive non-Foster circuit

NGD especially designed to accommodate passive NFC because of the relation between the NFC reactive elements and the NGD network. The main difference between the passive NFC and NGD as designed by Park et al. [7] is the bandwidth of the NGD. In general, the BW of NGD circuits as shown in Fig. 2, is narrow, but the NGD property is sink, as shown by Noto [8] and Siddiqui [9].

![Fig. 2. Negative group delay cell.](image)

However, the same property of passive NFC also exists in broadband and does not sink because it is interpolated from the phase of negative impedance, as shown...
in Eq. (1) and Fig. 1. A conventional NGD, shown in Fig. 2, is the combination of parallel RLC resonators and series RLC resonators. This combination results in greater loss parameter because the loss effect of many passive components; therefore, our passive NFC is designed according to Fig. 3.

To allow for the easy calculation of the series impedance of our passive NFC design, our circuit topology is reciprocal and symmetrical $\Pi$ type, as shown in Fig. 3. The non-Foster impedance ($Z_{NF}$) of our circuit can be calculated by using the scattering parameters (S-parameters) in the $S_{21}$ relation.

$$S_{21} = \frac{2Z_0}{2Z_0 + Z_{NF}} \Rightarrow Z_{NF} = \frac{2Z_0(1 - S_{21})}{S_{21}},$$  \hspace{1cm} (2)

From Eq. (1) and Eq. (2), it is clear that the link between non-Foster impedance and other parameters of NFC that can also explain the relation between the impedance of negative elements and the impedance of NFC. In addition, these equations also explain why the conventional NFC which has active components (like design of Linvill [10]) can become high Q NFC, like a practical negative lump components.

### 3 Simulation and measurement

In this section, the simulation and measurement results of our design and calculation of Non-Foster impedance are shown. Because we use small size (0402) lump components for reducing the loss from microstrip line in our circuit. Therefore, the circuit dimensions are $5\text{ mm} \times 9.5\text{ mm}$ on substrate Taconic TLC-32 as shown in Fig. 4. Our circuit simulation results are shown in Fig. 5 and were compared with the measurements results shown in Fig. 6; the loss and phase errors from this comparison are between $0.2$–$1.3\text{ dB}$ and between $0.5$–$0.2^\circ$, respectively.

The phase of passive NFC not pure compared with the ideal negative elements, between $-8.6^\circ$ and $-6.5^\circ$, as shown in Fig. 1 because the loss of passive lump components result in high resistance of passive NFC which results in phase changes in NFC, as shown in Eq. (1). To further validate the measurement results, we also show the NGD measurement results in the Fig. 7.
To find the negative impedance of our design, the $S_{21}$ was calculated from the measurement results of both the phase and loss by the following equation:

Fig. 4. Fabrication result of the $-5$ pF circuit.

Fig. 5. Simulation results of the $-5$ pF circuit.

Fig. 6. Measurement results of the $-5$ pF circuit.
where $|S_{21}| = 10^{(db(S_{21})/20)}$ is the magnitude of $S_{21}$, which can be calculated from the circuit loss. By substituting $S_{21}$ from Eq. (3) to Eq. (2), the Non-Foster impedance $Z_{NF}$ can be calculated. The negative capacitor value can be found by the reactance of $Z_{NF}$, as shown in Table I.

| Frequency | $S_{21}$ | $Z_{NF}$ | Capacitor value |
|-----------|---------|----------|-----------------|
| 2.1 GHz   | $(0.54 - 0.047j) + 82.35 + 15.63j$ | $-4.85 \text{ pF}$ |
| 2.5 GHz   | $(0.55 - 0.037j) + 82.79 + 12.26j$ | $-5.19 \text{ pF}$ |
| 2.9 GHz   | $(0.59 - 0.038j) + 69.67 + 10.91j$ | $-5.02 \text{ pF}$ |

Table I shows that the ratio between reactance and the resistance of the passive NFC, which is the Q factor of the passive NFC, is small. This is the main reason that passive NFC, a special type of broadband NGD, is not reliable in terms of its negative elements.

4 Conclusion

We have proposed a novel passive NFC with $-5 \text{ pF}$ negative impedance from 2.1–2.9 GHz. In our design, we only used lump components and we improved it by reducing the number of unnecessary lump components. The results proved that we can design a limited Q-factor NFC without supply power. In the future, we will use only one active component to design a new NFC which will act as a practical $-5 \text{ pF}$ capacitor.

Acknowledgments

This work was supported by the Basic Research Laboratory (BRL) through an NRF grant funded by the MSIP (No. 2015056354).