DESIGNING A REFLECTION-TYPE NGD NETWORK USING OPEN AND SHORT SHUNT STUBS FOR WIDEBAND ELECTRICALLY SMALL ANTENNAS

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Abstract

Wireless communication devices such as mobile phones play a vital role in our daily life. They need to cover an increasingly wide frequency band with low profile antennas. Electrically small antennas (ESAs) comply with these requirements. However, they are subject to gain-bandwidth limits when matched with passive matching networks. Non-Foster reactive elements have been proposed to bypass those restrictions. This paper addresses designing negative group delay NGD-based non-Foster networks to overcome stability problems when using Negative Impedance Converters (NICs) in order to realise on-Foster reactive circuits. The NGD network model was designed using open short stubs to achieve a non-Foster behaviour, and to act as a negative capacitor in the frequency range of interest. This technique of compensating the inherent loss of the proposed NGD network in the reflection mode was to realise a new structure of reactive non-Foster elements. It involves a negative resistance amplifier and a Lange coupler. The proposed technique is applicable to antenna matching where both transmit and received capabilities are required. It was simulated and the experimental results of the new NGD network circuit were introduced.

Keywords: NGD networks; Non-Foster reactive networks

Introduction

Foster's reactance theorem means that for any passive elements such as positive capacitors and positive inductors, the associated reflection coefficient S_{11} rotates clockwise (WS) on the Smith chart with an increasing frequency and always has positive slopes as shown in Figure (1, a) (Almahroug et al., 2016).

On the other hand, Non-Foster reactive elements are the artificial structures whose reactance characteristics violate the condition of Foster's reactance theorem. These elements are characterised by a negative reactance slope as the frequency increases. The associated reflection coefficient rotates counter-clockwise (CCW) around the Smith chart with an increasing frequency as depicted in Figure (1, b). The most common non-Foster elements are the negative inductors and the negative capacitors (Nauwelaers et al., 2013).

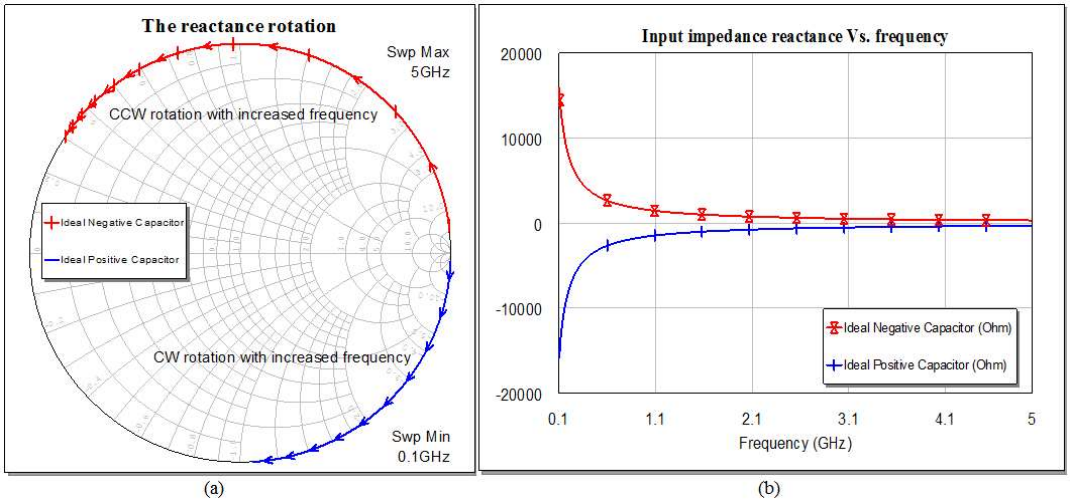


Figure (1): (a) the reactance rotation of Foster and non-Foster elements around the Smith chart; (b) the reactance slope vs. Frequency.

Realisation of Non-Foster Impedances

Non-Foster reactive impedances are usually realised by active circuits that are called Negative Impedance Converters (NICs) and Negative Impedance Inverters (NIIs). Linvill proposed the first floating and grounded NICs; they were implemented using transistors in 1954 (Sussman-Fort and Rudish, 2009). The NIC model that comprised two transistors is shown in Figure (2).

The principle idea of generating a negative behaviour of a passive load (i.e. capacitor or inductor) is to swap sensing points of the reactive impedance and measuring the voltage across it. Therefore, if some current passes through an impedance element (i.e. capacitor or inductor) and the voltage is measured across it, then its positive impedance can be measured. On the other hand, if we swap over the AC voltage measurement probes, we measure the negative impedance because the current is still the same and the voltage is reversed.

This concept applies to Linvill's circuit where the feedback paths are swapped over and the voltage is sensed through the gates of the transistors; the current does not change, but the sensing points, where the voltage is measured, change because the voltage is reversed. The impedance inversion of Linvill's NIC analytically was proven in (Nauwelaers et al., 2013).

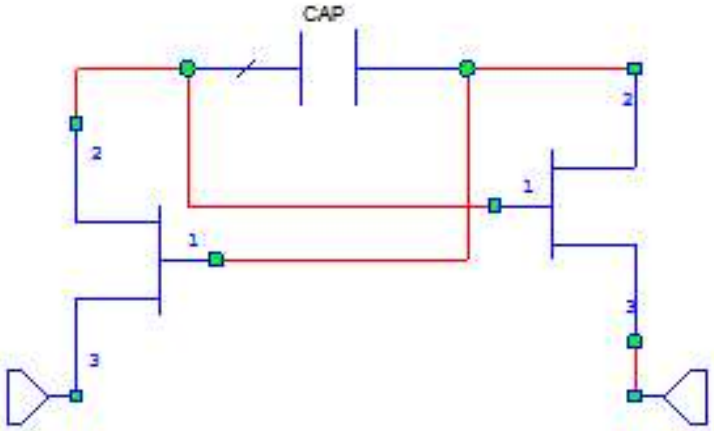


Figure (2): Ideal Linvill NIC Realising a Negative Capacitor.

The biggest challenge when designing non-Foster circuits using NICs is stability because of the negative impedance production and the controlling difficulty of circuitry feedback. So, it is necessary to assess the stability of the whole system including the NICs (Almahroug et al., 2016).

Non-Foster Elements Applications

There is an increasing demand for small wide-band antennas for wireless communication devices such as mobile phones and electronic devices that need to cover large frequency bands with a compact antenna. Wheeler and Chu consider an antenna as electrically small if the wavelength is bigger than its physical length. The Q-factor of a small antenna is inversely proportional to its electrical size and it increases inversely with the third power of electrical length i.e. these antennas are characterised by a high reactive (high-Q) input impedance and a large reactance. The following equation presents the relation between the small antenna radiation quality factor (Q) and its electrical length (kr) (Sussman-Fort and Rudish, 2009):

$$Q=1/(kr) \qquad (1)$$

Regardless of their shape and type, ESAs are characterised by a high reactive (high-Q) input impedance and a large reactance (Sussman-Fort and Rudish, 2009). The problem is transferring power to and from them, which consequently makes them very difficult to match. Although there are applications and systems that require

wideband small antennas, these physical limits hinder developing wideband small ones. Therefore, matching networks are needed to match antenna radiation resistance to the transmission line.

The input impedance of an electrically small antenna is dominated by a capacitive reactance below its resonance and a relatively narrow operational bandwidth. Impedance can be matched to the desired frequency to deliver the maximum amount of energy to arbitrary load impedance through using an external passive inductor see Figure (3, a). An inductor has a reactance, which can negate the effect of a capacitive reactance of the electrically small antenna. Therefore, by adding them in a series, their reactance swill cancel each other; this will result in a perfectly matched system where the whole energy is delivered to the resistor without any unwanted stored energy in the inductor or the capacitor. The problem here is that a perfect impedance match occurs only at a single frequency and results in a very limited bandwidth and gain. This gain-bandwidth limitation was reported by Bode and Fanoin (Almahroug et al., 2016).

Figure (3, b) illustrates the anomalous reactance characteristic of a non-Foster reactive element (such as a negative capacitor); it provides a complete cancellation of the reactance of an electrically small antenna over a large frequency bandwidth. The non-Foster impedance matching technique was proposed to bypass the restrictions of the gain-bandwidth theory that inhibit continuous broadband passive matching of antennas (Almahroug et al., 2016, Nauwelaers et al., 2013, Sussman-Fort and Rudish, 2009).

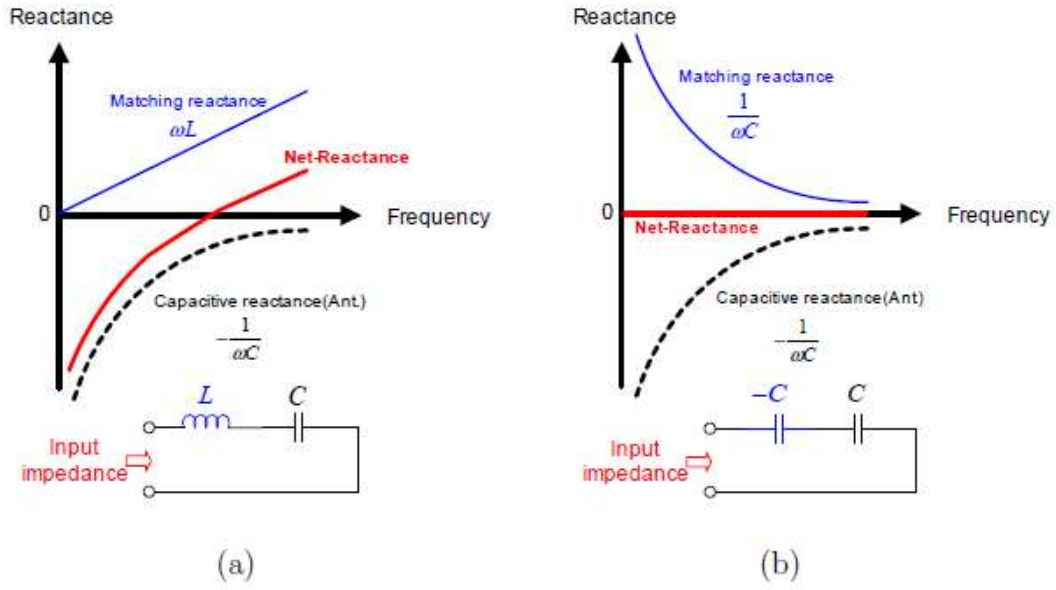


Figure (3): An Antenna Matched with (A) a Passive Matching Network (B) with a Non-Foster Matching Network (Sussman-Fort and Rudish, 2006).

Most of the recently published works have employed negative capacitors realised by NICs as a non-Foster matching network with electrically small antennas. Susman-Fort mentioned the use of non-Foster impedance matching networks with electrically small dipole and monopole antennas within transmission and reception applications. However, the matched antennas had low top frequencies within the HF and the VHF regions (Sussman-Fort and Rudish, 2009, Sussman-Fort and Rudish, 2006). Interestingly, none of these papers tackled network stability concerns.

Tade proposed a NIC structure that operates as a negative capacitor at 1.5 GHz. The NIC circuit was used as an on-Foster matching network with a chassis antenna to achieve wideband antenna performance. To the best of our knowledge, it has been the highest achieved frequency reported in literature so far. The main reason for the few successful demonstrations reported beyond VHF bands is the stability issue associated with the NICs that arises from generating negative impedances and form circuitry feedback control difficulty at higher frequencies (Nauwelaers et al., 2013).

In addition to impedance matching, non-Foster reactive elements have been implemented in many other applications. For example in electromagnetic applications, the bandwidth of artificial magnetic conductors (AMCs) was increased when non-Foster circuits were loaded (Gregoire et al., 2011, Kern et al., 2003).

Basic Theory of Negative Group Delay

Negative group delay (NGD) occurs when a signal passes through a suitably configured network in a forward or a backwards direction (Almahroug et al., 2016). Such networks can be either transmission-type or a reflection-type. This network is commonly characterised by the RLC circuits which are cascaded in series and/or parallel fashions. The existence of NGD behaviour can be determined analytically from the phase response of the S-parameters of the circuit. An increasing phase with frequency in a specific frequency range indicates an NGD response (Almahroug et al., 2017). There are other methods for performing NGD networks exist in the literature (Mirzaei and Eleftheriades, 2013).

Relationship Between NGD Networks and Networks with Non-Foster Behaviour

The logical relation that connect the networks with an NGD response and the networks with non-Foster behaviour was explored and presented in (Mirzaei and Eleftheriades, 2013). They stated that to establish such a relationship, networks with NGD responses must represent reactive non-Foster elements at certain bandwidths, and networks that exhibit non-Foster reactance must operate as networks with NGD responses.

If a non-Foster reactive element is represented by its reactance X or susceptance B, these properties will be characterised by negative slopes and can be expressed by the following equation (Mirzaei and Eleftheriades, 2013):

$$\frac{\partial X}{\partial \omega} < 0 \quad and \quad \frac{\partial B}{\partial \omega} < 0 \qquad (2)$$

The reflection coefficient (S11) associated with these reactive circuits rotates anti-clockwise on the Smith chart with frequency as depicted in Figure (4, a). Moreover, the presence of the negative group delay (NGD) is observed from the synthesised phase response of S11 (Fheleboom, 2019). An increasing phase from f1 to f2 implies an NGD behaviour. Meanwhile, the network response below f1 and above f2 is a Foster response with a decreasing phase response versus an increasing frequency, as shown in Figure (4, b). The NGD networks exhibit losses which can be compensated using amplifiers. Loss-compensated NGD networks in a bandwidth of interest satisfy the condition of equation (2), (Mirzaei and Eleftheriades, 2013, Fheleboom, 2019).

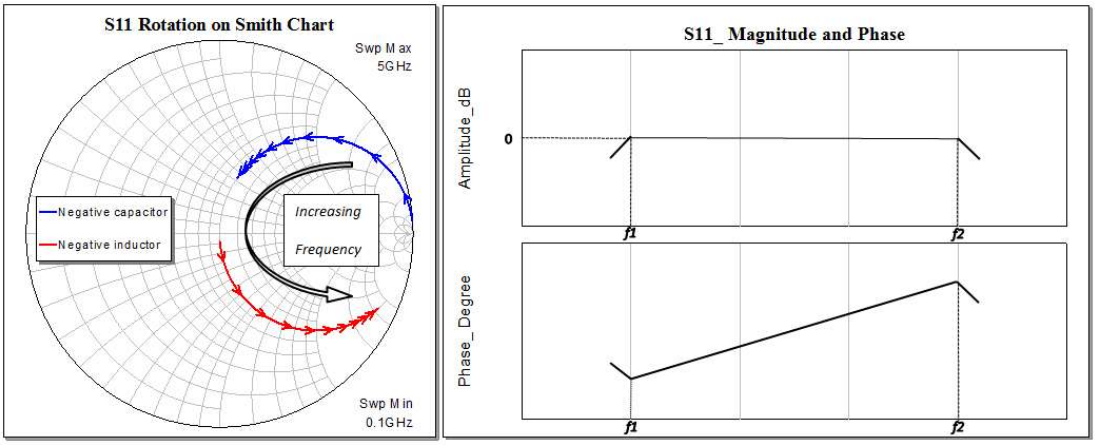


Figure (4): (A) S11 Rotation of Non-Foster Elements on Smith Chart; (B) Complex S11 Response of a Reflection –Mode NGD Network Shows an Increasing Reflection Phase from F1 To F2 With Zero Loss Amplitude.

By establishing this two-way relationship, new designing and implementation techniques of non-Foster circuits that use NGD networks were introduced. These approaches can obtain the non-Foster property mainly by using passive circuits. Thus, they have less stability concerns compared to the traditional methods using NICs. Transmission-type NGD networks were employed to realize non-Foster elements, and regular amplifiers were used to compensate for the losses in the NGD networks (Mirzaei and Eleftheriades, 2013).

Design of Reflection–Type NGD Network Using Open and Short Shunt Stubs

A novel approach for the implementation of stable NGD-based non-Foster reactive circuits was presented in (Almahroug et al., 2016). NGD networks in the reflection mode were designed by employing LC lumped elements in multiple parallel and series stages along with transmission line forming a lossy filter network with counter-clockwise phase response as depicted in Figure 5. These resonance circuits exhibit an NGD behaviour from 1 GHz to 2 GHz. However, implementing lumped elements such as capacitors, inductors and resistors in the design of NGD network has some limitations such as poor quality at high frequencies as well as mechanical implementations difficulties when soldering these lumped elements.

To reduce the complexity of the NGD structure of Figure (5), and to overcome the aforementioned limitations on designing the NGD network using LC resonators, an alternative approach based on implementing the shunt LC resonators as open and short transmission line stubs will be introduced in this paper for the first time.

To design open and short stubs which act as capacitors and inductors, the electrical length (θs) of the stubs must be determined from known capacitors and inductors values. The entire design is based on analytical equations that demonstrate how the electrical lengths of the open and shorted circuited stubs are calculated. To avoid density, the analytical equations were not introduced here. AWR microwave office was used to design the subs-based NGD circuit then it was structured and experimentally tested. The scheme and the image of the proposed NGD circuit are depicted in Figures (6) and (7) respectively.

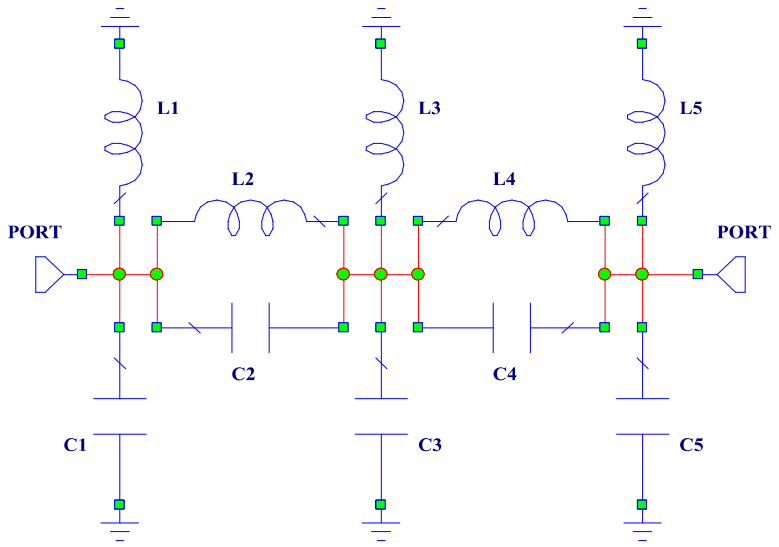


Figure (5): Circuit Schematic of the Ideal Reflection-Mode NGD Network (Almahroug et al., 2016).

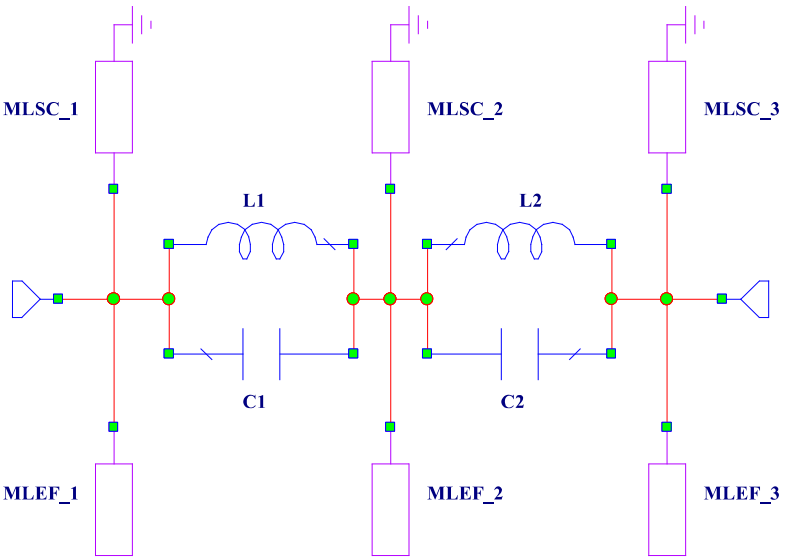


Figure (6): Circuit Schematic of the NGD Network Realised Using Ideal Components, Where, MLSC Denotes the Short Microstrip Line Stub and MLEF Denotes the Open Microstrip Line Stub.

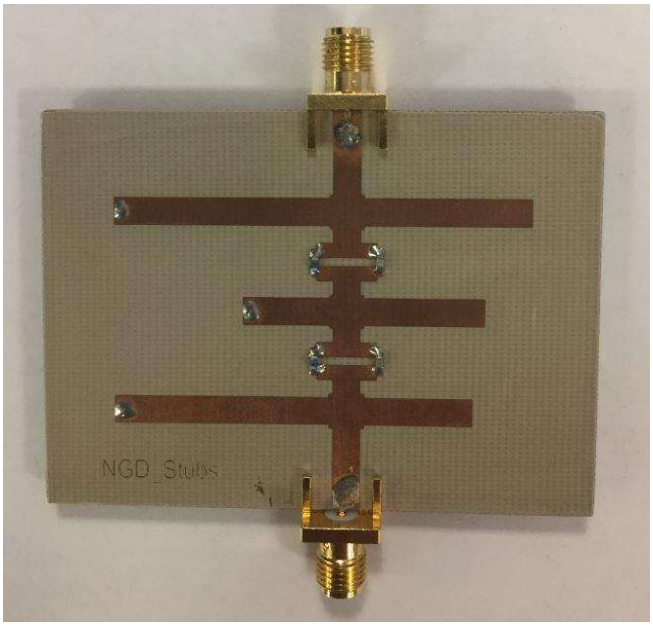


Figure (7): Image of the Proposed NGD Network Prototype.

Figure (8) illustrates the simulated and measured results of S11 magnitude and the phase of the proposed NGD network. Both results are in a good agreement and show NGD behaviour with a positive reflection phase gradient with frequency from 1.32–

1.48 GHz by 25.7 degrees. Studying the S-parameters of both reflection-type NGD networks reveals that the phase of S11 is an increasing function of frequency, and it implies a non-Foster behaviour at that bandwidth. However, this NGD network was of a "lossy" structure and had about 8 dB loss which needed to be compensated.

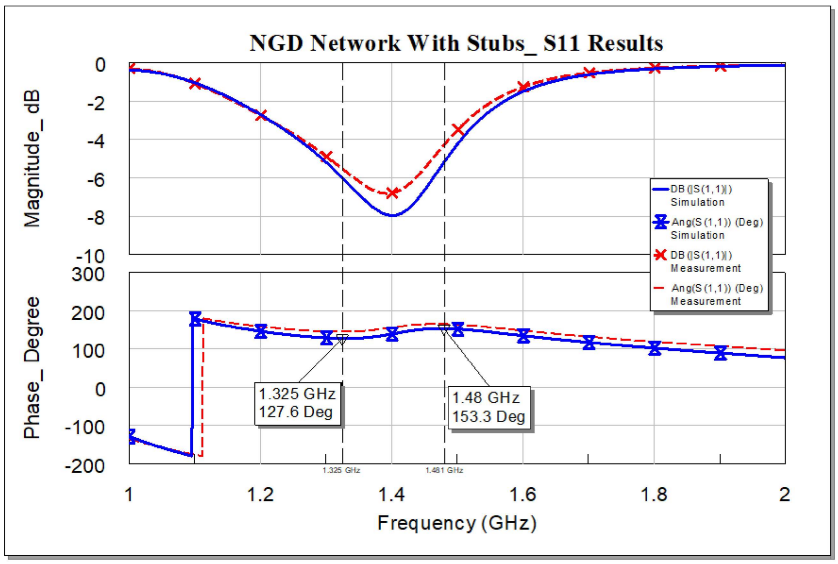


Figure (8): Simulated and Measured Results of S11 Magnitude and Phase of the Reflection-Type NGD Network Realised Using Stubs.

The obtained group delay (GD) results from both the simulation and the measurement are being compared in Figure (9). Both results generated an NGD level of about -0.65ns, and a bandwidth of 0.16 GHz negative group delay in the bandwidth of interest. Table (1) shows a comparison between the measurement results of the proposed NGD network using stubs and the NGD network proposed by (Almahroug et al., 2016), in terms of the realisable bandwidth, losses, reflection coefficient's phase and group delay.

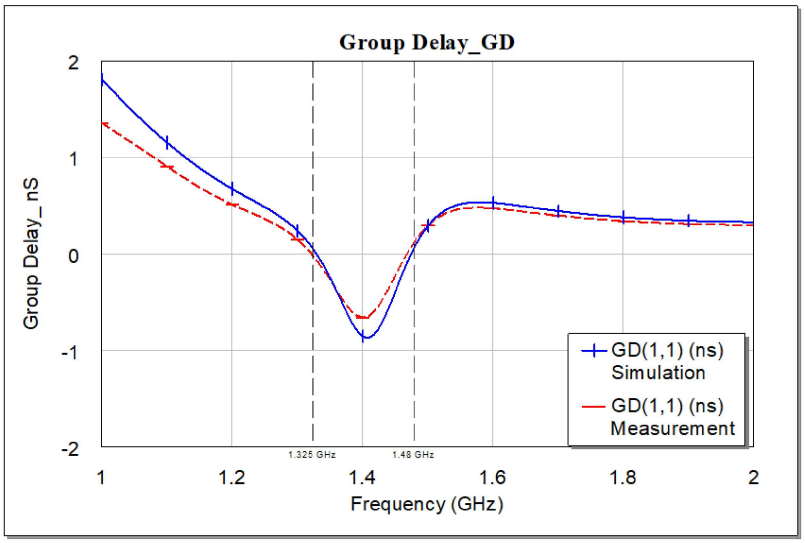


Figure (9): Simulated and Measured Group Delay (GD) Responses Obtained from Realistic Reflection-Type NGD Network Using Stubs.

Table (1): Summary of the Performance of the Realised Reflection-Mode NGD Networks Using Stubs with NGD Network Realised in Ref (Almahroug et al., 2016).

Prototype	Realisable NGD Bandwidth	Losses dB	S11 Phase increased by	Group delay
The proposed NGD network in this paper	116 MHz between 1.32- 1.48 GHz	8 dB	25.7 degrees	-0.65 ns
The proposed NGD network in ref (Almahroug et al., 2016)	170 MHz between 1.2- 1.37 GHz	10 dB	27.3 degrees	-1.62 ns

Studying the S-parameters of both reflection-type NGD circuits revealed that the phase of S11wasan increasing function of frequency, which implies a non-Foster behaviour at that bandwidth. Both reflection-types, NGD networks using stubs and LC resonators, exhibited an NGD behaviour of -0.65 ns over a bandwidth of 0.16 GHz and -1.62 ns over a bandwidth of 0.3 GHz respectively.

A new perspective in the realisation of NGD networks that are with zero loss in a certain bandwidth, which involves a reflection amplifier and a Lange coupler for compensating the losses of the proposed stubs-based NGD network will be presented in section below.

Synthesised non-Foster Circuit using Loss-Compensated Stubs-Based NGD Networks

The new loss compensation scheme involves three separate components in the realisation of the final NGD-based non-Foster network. The concept of this loss compensation technique was firstly introduced in (Almahroug et al., 2016, Almahroug et al., 2017). It is characterised by combining the NGD networks and a negative resistance reflection amplifier in a balanced structure with a Lange coupler. All individual elements were modelled, fabricated and experimentally tested to validate their theoretical concepts. For the sake of simplicity, testing results of the corresponding individual components were not presented here. All the aforementioned components were combined together to construct a new structure which behaved as a reactive non-Foster element (particularly a negative capacitor) in a limited bandwidth within the microwave frequency region. Within this novel design, the overall NGD response was provided by separate passive circuits which had no stability concerns.

The overall NGD-based non-Foster structure was designed, simulated and optimised using AWR Microwave Office. The schematic of the NGD-based non-Foster network is presented as sub-circuits in Figure (10).

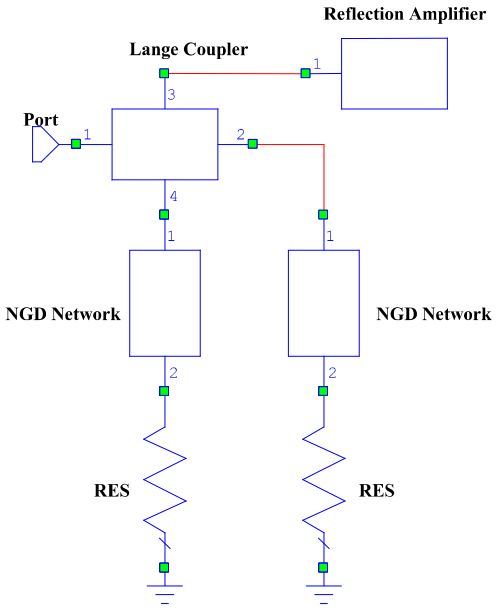


Figure (10): A Circuit Schematic Demonstrates the Loss Compensation Technique to Obtain the Synthesised Non-Foster Reactive Element. All the Components are Presented as Sub Circuits (Almahroug et al., 2016).

The S11 magnitude and phase results of the overall structure are illustrated in Figure (11). There is an increasing reflection phase with a positive slope which means that the circuit exhibited a non-Foster behaviour in that specific bandwidth. Furthermore, the amplitude of the reflection coefficient was very close to 0 dB in the frequency region of interest. It appears that the proposed loss compensation technique was working properly since the losses of the NGD networks were compensated and the resulting loss free non-Foster reactive circuit was working as a negative capacitor in that limited bandwidth.

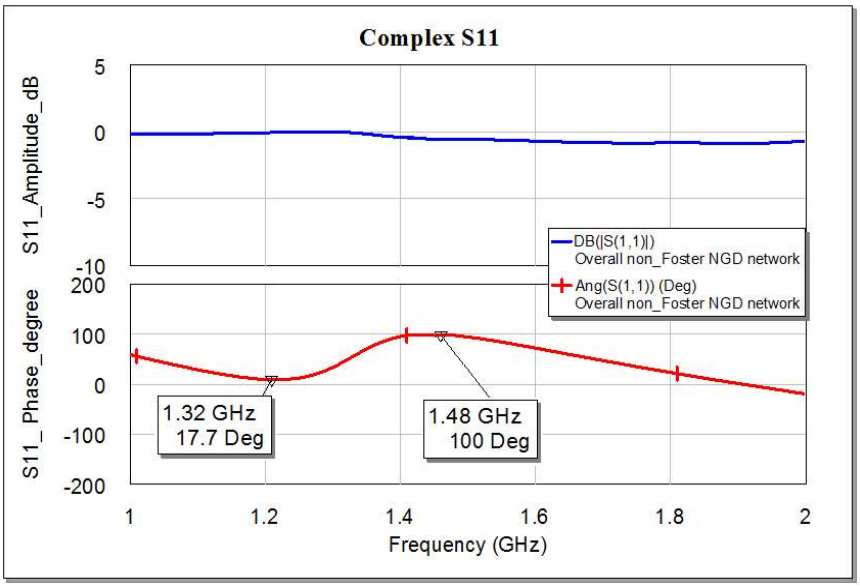


Figure (11): Reflection Coefficient S11 Response Plots for the Overall Non-Foster NGD Network.

Finally, the stability of the proposed NGD-based non-Foster circuit was checked using the Nyquist. Stability was measured with a modified gamma-probe (STABN_GP2). The measurement available in NI AWRDE Microwave Office shows that the circuit was stable, see Figure (12).

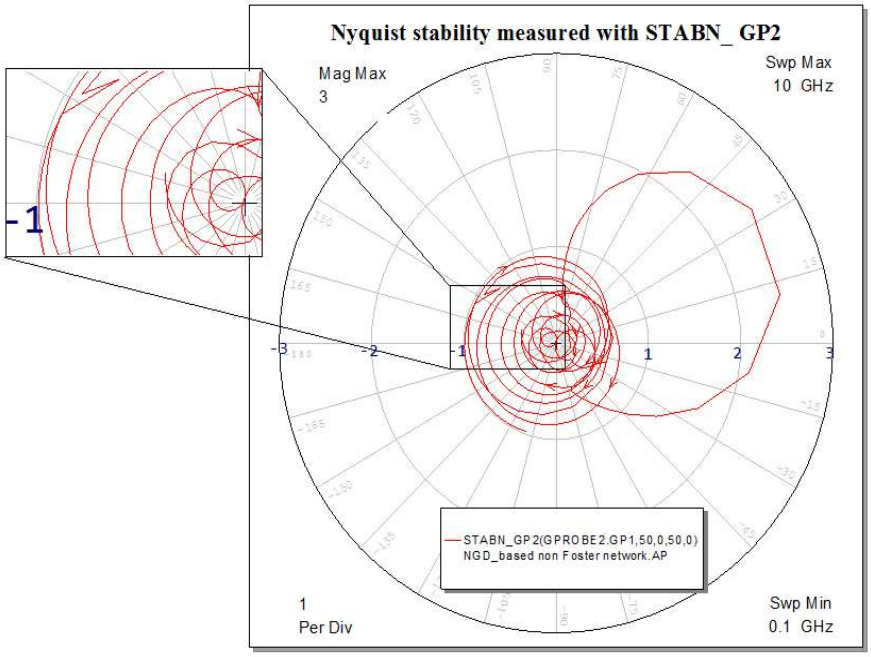


Figure (12): Nyquist Diagram to Detect the Instability of the FET-Based Reflection Amplifier. The Open Loop Function G Does not Encircle the -1 Point in the Clockwise Direction, thus, the NGD-Based Non-Foster Circuit is Considered Stable.

The new design can be used as a non-Foster matching network with small electrical antennas in order to enhance their bandwidth. The proposed technique applies to antenna matching where both transmit and receive functions are required.

Conclusions

This paper presented a new class of non-Foster reactive elements in the microwave frequency band, and presented a new structure of a reflection-mode NGD network using open and short stubs. This resonance circuit exhibited an NGD behaviour with an NGD bandwidth of 116 MHz and a positive reflection phase gradient with frequencies from 1.31 GHz to 1.48 GHz by 25.7 degrees. Experimental results of the proposed stubs-based NGD network were compared with the same results obtained from an NGD network realised using LC resonators in (Almahroug et al., 2016). Studying the S-parameters of both reflection-type NGD networks revealed that the phase of S11wasan increasing function of frequency, which implies a non-Foster behaviour at that bandwidth. Both circuits acted as a negative capacitor in the frequency range of interest. By combining two of the proposed NGD networks and a negative resistance reflection amplifier with a quadrature hybrid coupler in a balanced structure, the researchers introduced a new loss compensation method in NGD networks. Simulation results from the final circuit showed that this novel technique could compensate the losses of the proposed NGD network in the target

frequency range by the amplification obtained from the reflection amplifier. Although the reflection amplifier has its own stability issues, this separation of functions into separate elements makes it easier to establish more stability than that in the conventional NIC approach. The potential use of a synthesised non-Foster circuit in antenna matching applications is considered as a future work.

Acknowledgment

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