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Signal-Interference-Based Structure with Negative Group Delay Properties

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***Abstract*—In this work, a signal-interference-based structure with negative group delay (NGD) properties is proposed. The proposed topology allows an easy control and design of the NGD characteristics, such as the group delay GD at the design frequency, the NGD bandwidth (NBW) and the maximum attenuation. For that purpose, some design closed-form expressions have been analytically obtained and design curves have been provided. The circuit sensibility as a function of the design parameters is also studied. In order to demonstrate the capabilities of the proposed structure, a proof-of-concept circuit has been designed and implemented to be centered at 1 GHz. It has shown a very broad NBW of 320 MHz, with a NGD of -0.8 ns at 1 GHz and a maximum attenuation of 15 dB.**

I. Introduction

Recently, a renewed interest in negative group delay (NGD) networks at microwave frequencies is being observed. This phenomenon is attributed to the positive phase slope or phase advancement of the propagating signal in a circuit. The NGD effect appears within a limited frequency band when the absorption or attenuation is at a maximum, therefore, NGD networks are generally based on bandstop structures. This physical effect does not contradict the causality principle because the initial and final transient signal pulses are still limited to the front velocity, which will never exceed the speed of light [1], [2]. In fact, a device presenting such characteristics may be considered as a "predictor" network, since the signal at its output is in time advance with respect to that at the input. For this behaviour, the input signal bandwidth should be limited to the circuit NGD bandwidth (NBW), i.e., it should be redundant, otherwise, the output signal will lose the shape of the input one.

The NGD network has been applied in several communication systems for increasing the efficiency of feed-forward linearization amplifiers, shortening delay lines, or minimizing the beam-squint in phased array systems [3]. Several approaches have been used for the design of microwave NGD circuits, such as the use of active RLC resonators [2], [4]. To increase the operation frequency, distributed topologies by using transmission line resonators along with resistors and coupled lines [3], [5]–[8] as well as active transversal filters [9] have been recently proposed. However, NGD passive devices are systematically accompanied by high signal attenuation, narrow NBW and/or response flatness problems, consequently, all efforts are being focused on improving those characteristics.

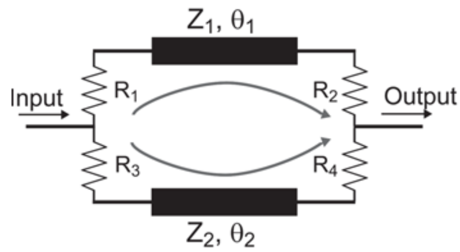


Fig. 1. Schematic diagram of the proposed signal-interference-based structure with negative group delay characteristics.

In this work, a simple structure is proposed in order to obtain NGD characteristics. This network is based on a signal interference filter formed by two transmission lines arranged in parallel creating two signal paths [10]–[12]. This structure enables an easy and fast design in terms of NGD performances. For verification purposes, a proof-of-concept device is designed and implemented to be centered at 1 GHz. The implemented device has shown a NBW of 320 MHz with a NGD of -0.8 ns at 1 GHz and a maximum attenuation of 15 dB.

II. Description and Analysis of the Proposed Structure

Fig. 1 shows the proposed signal-interference-based structure with potential to obtain transfer functions with negative group delay responses. It is formed by two transmission lines arranged in parallel creating two signal paths. The two transmission lines, with characteristics impedances and electrical lengths Z_1 and θ_1, and Z_2 and θ_2, respectively, present a phase shift of 180^o at the design frequency f_0. In this way, the signal at the input port, is divided into two subcomponents which arrive with opposite phase at the output port, leading to a bandstop-filter behaviour, where a pair of finite transmission zeros is symmetrically generated around f_0. Four resistors, R_1, R_2, R_3 and R_4 are added at the connection points between lines. The function of these resistors is, by adding losses to the structure, to convert the phase singularities at the stopband, inherent to a bandstop-type structure, into soft phase responses with positive slope, which lead to the phenomenon of negative

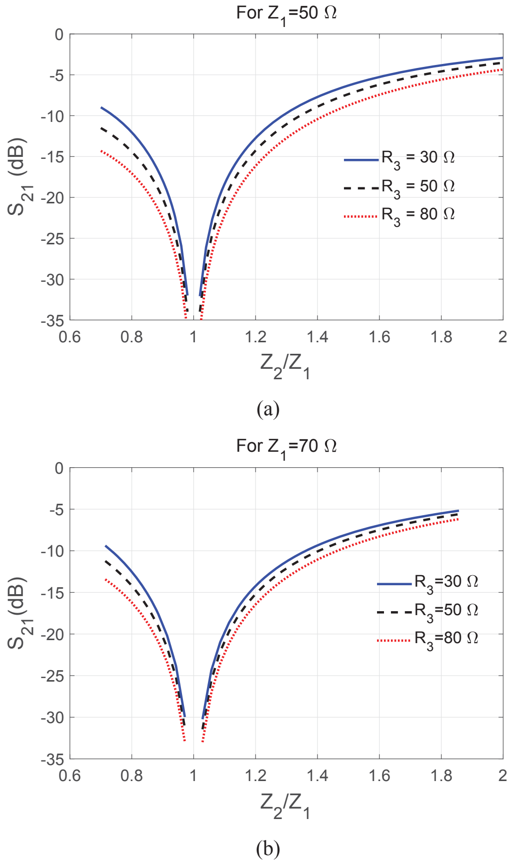


Fig. 2. S_{21} parameter at $f_0 = 1$ GHz as a function of Z_1, Z_2 and R_3. a) For $Z_1 = 50$ Ω. b) For $Z_1 = 70$ Ω.

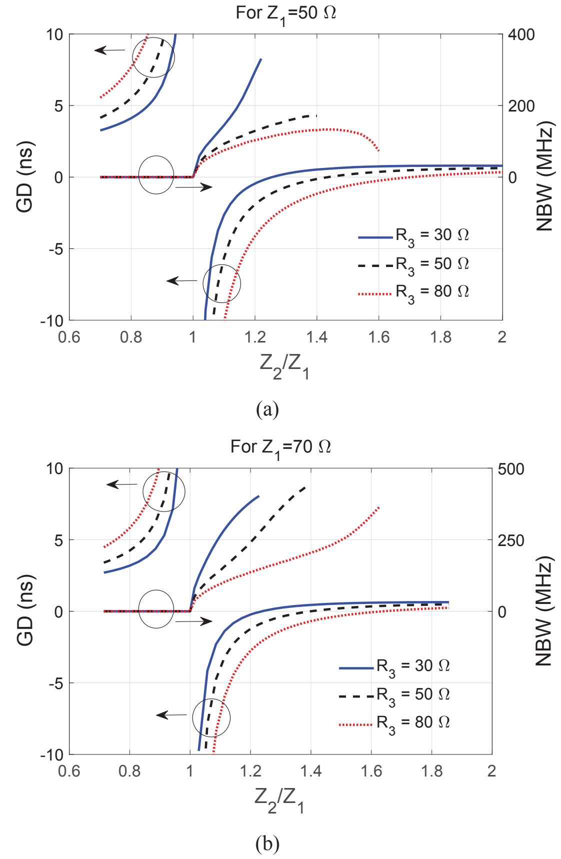


Fig. 3. GD at $f_0 = 1$ GHz and NBW in MHz as a function of Z_1, Z_2 and R_3. a) For $Z_1 = 50$ Ω. b) For $Z_1 = 70$ Ω.

group delay. Taking into account that the electrical lengths θ_1 and θ_2 are fixed to 90^o and 270^o in order for the structure to have a bandstop behaviour –as previously discussed–, the proposed network still presents six free design parameters, which makes its mathematical analysis very hard. Since it is convenient to minimize the number of lumped components, it is assumed $R_1 = R_2 = R_4 = 0$ Ω. As a consequence, there are just three design parameters Z_1, Z_2 and R_3, which make possible the control of the negative group delay characteristics in an easy and effective way.

The performance of a negative group delay network can be defined by the following three parameters: negative group delay NGD at f_0, negative group delay bandwidth NBW and attenuation at f_0. The ideal features of a NGD network are to have a NGD as negative as possible, in a wide bandwidth, along with a minimum attenuation. However, these three characteristics go into different senses. For example, increasing NGD implies minimizing the NBW and/or increasing the attenuation. Therefore, a trade-off among these three parameters should be found, depending, of course, on the specifications.

Under the aforementioned assumption regarding the resistors, the S_{21} parameter can be analytically found at f_0 as

$$S_{21}(f_0) = \frac{-j\frac{2}{Z_0}\left(\frac{1}{Z_1} - \frac{1}{Z_2}\right)}{\left(\frac{1}{Z_0}\left(\frac{1}{Z_0} + \frac{R_3}{Z_2^2}\right) + \left(\frac{1}{Z_1} - \frac{1}{Z_2}\right)^2\right)}. \quad (1)$$

The analytical computation of the group delay is considerably harder than that of insertion loss. Herein, in order to be able to find a closed expression for the group delay, the S_{21} parameter of the proposed network has been approximated around f_0 by means of a first-order Taylor Series. In this way and after some algebraical manipulation, the following expression for the group delay at f_0 is found as

$$\text{GD}\left(f_0\right) = -\frac{\partial\phi(f)}{2\pi\partial f} = \frac{N_1 - N_2}{D}, \quad (2)$$

where ϕ is the phase response of S_{21} and

$$N_1 = Z_1\left(3R_3^2 Z_1/Z_0 + R_3\left(3Z_1^2 Z_2/Z_0^2 + 4Z_1 - 4Z_2\right)\right), \quad (3)$$

$$N_2 = -2Z_1 Z_2/Z_0\left(-3Z_1^2 + 2Z_1 Z_2 + Z_2^2\right) \quad (4)$$

and

$$D{=}4f_0(Z_1 - Z_2) \cdot \left[Z_1^2\left(R_3/Z_0 + Z_2^2/Z_0^2 + 1\right) - 2Z_1 Z_2 + Z_2^2\right]. \quad (5)$$

Expressions (1) and (2) can be used to obtain several design curves. Figs. 2 and 3 show the S_{21} parameter and the GD at $f_0 = 1$ GHz, as a function of the three design parameters involved in the topology. As those figures show, $Z_1 = Z_2$ produces a singularity in the topology response, and as a

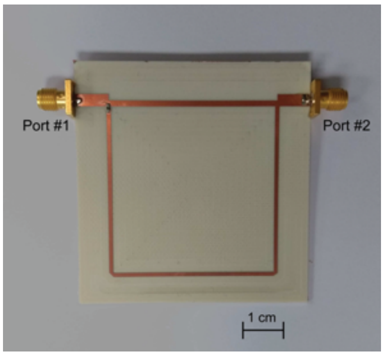


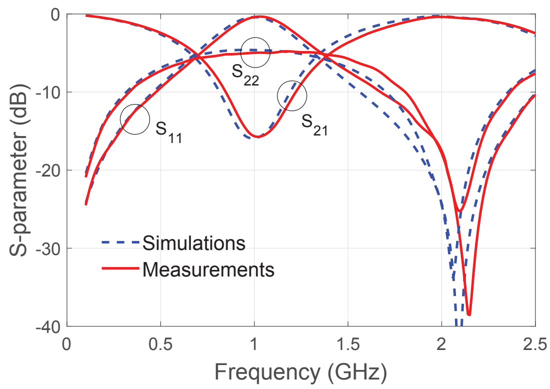
Fig. 4. Photograph of the implemented NGD network.

consequence, it should be avoided. It is also observed that, high NGD values will imply high insertion loss levels (> 20 dB), as one may expect. Another interesting aspect which can be obtained from these figures is the sensibility of the topology as a function of the design parameters. It is seen that for $Z_2/Z_1 < 1.1$, both S_{21} parameter and GD vary very fast. Thus, this range should be avoided even if very NGD values are being looked for. Otherwise, typical PCB process tolerances, of around 50 μm in the strip-width, may produce a big change in the expected GD and S_{21} values.

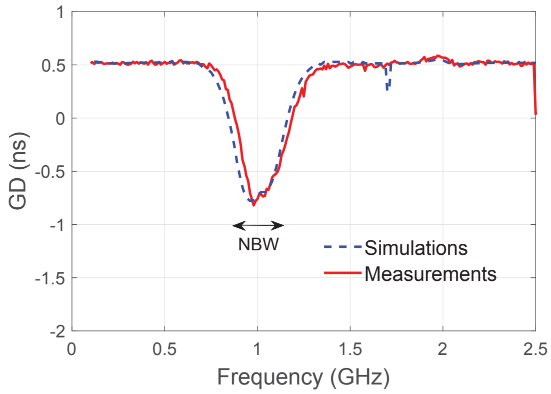
Fig. 3 also shows the NBW as a function of the design parameters. The upper limits of the NBW curves correspond to the case where the ripple in the inband GD response makes the GD at f_0 be positive. In this figure, it is also clearly observed that high NGD values will imply narrow NBW. By comparing Figs. 3(a) and (b), one can see that for $Z_1 = 70\ \Omega$, wider NBWs are obtained that those for $Z_1 = 50\ \Omega$. On the other hand, from Figs. 2 and 3 it can be concluded that R_3 plays an important role regarding the GD characteristcs, however, its influence with respect to the attenuation is minimum. Therefore, in the design phase, Z_2/Z_1 should be firstly chosen to adjust the attenuation at f_0. And once Z_2/Z_1 is selected, the GD and NBW will be controlled by Z_1 and R_3.

III. Experimental Results

In order to validate the proposed topology, a NGD device has been designed and implemented at $f_0 = 1$ GHz. The circuit has been fabricated on RO4003 substrate from Rogers®, which presents the following characteristics: $\epsilon_r = 3.55$, loss tangent $\tan\delta = 0.002$, thickness $h = 1.52$ mm and copper layer thickness $t = 20\ \mu$m. The proof-of-concept device has been designed to have a broad NBW of 350 MHz, with a maximum attenuation of 15 dB and with a moderate NGD of around 1 ns at 1 GHz. The design parameters in order to obtain these characteristics are found from Figs. 2 and 3 to be $Z_1 = 76\ \Omega$, $Z_2 = 90$ and $R_3 = 39\ \Omega$ (it corresponds to a commercial value). Fig. 4 shows the photograph of the implemented circuit whereas its simulated and measured responses are plotted in Fig. 5. The simulations have been performed by means of the full wave simulator Sonnet and it has not been needed any optimization process. As seen from Fig. 5, there has been a good agreement between simulations and measurements. The measured S_{21}, GD and NBW have been -15.7 dB, -0.82 ns and 320 MHz, respectively.



(a)



(b)

Fig. 5. Simulated and measured responses of the implemented circuit. a) S-parameter. b) Group delay.

The proposed structure has been exposed to a possible communication system scenario. For that, a random digital signal modulated by means of a Gaussian minimum shift keying (GMSK) modulation with a carrier frequency of 1 GHz, and with a bit rate of 100 Mbps has been applied to the circuit. Fig. 6 shows the input and output voltage signals, where it is clearly observed that the output signal is predicted with around 1 ns in advance. It is also shown that during the first intervals of time (< 5 ns), i.e. during the transient time, the output signal does not have the shape of the input signal, as expected, since causality is preserved.

A. Future work

The implemented NGD structure has demonstrated good performances in terms of NGD, NBW and attenuation, as demonstrated in the previous section. In addition, the assumption $R_1 = R_2 = R_4 = 0$ has allowed us to get closed-form expressions for an easy and fast design. However, this assumption makes the structure response not be matched simultaneously at both ports, as seen from Fig. 5. If the aforementioned assumption is relaxed, e.g. $R_4 \neq 0$, it may be possible the design of a NGD signal-interference-based structure matched at both ports. Fig. 7 shows some preliminary

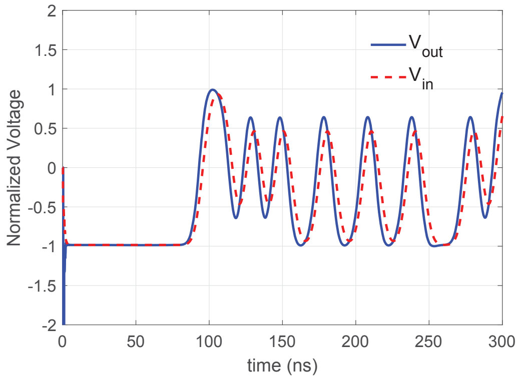
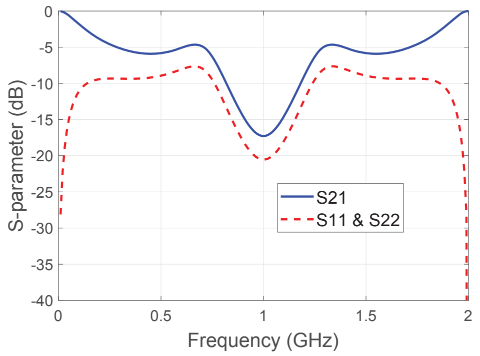
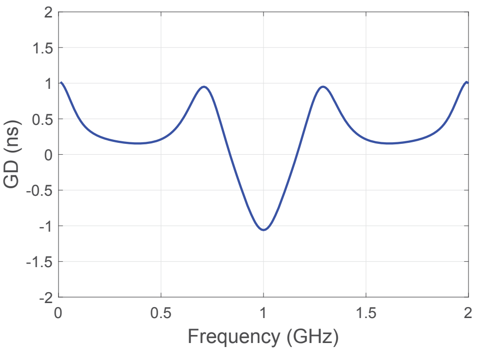


Fig. 6. Comparison between the input and output voltage signals when a 100 Mbps GMSK signal with a carrier frequency of 1 GHz (not shown for clarity) is applied to the proposed circuit. Results obtained by simulation by using the measured S-parameters from the implemented device.



(a)



(b)

Fig. 7. S-parameters (a) and GD (b) ideal responses of the suggested structure with $Z_1 = 80\ \Omega$, $Z_2 = 25\ \Omega$, $R_3 = R_4 = 50\ \Omega$ and $R_1 = R_2 = 0\ \Omega$.

results (circuital simulation) where a very good matching is found at both ports with NBW = 350 MHz, GD = -1.0 ns and $S_{21} = -17$ dB.

IV. Conclusions

A NGD circuit based on a signal-interference topology has been demonstrated in this paper. The structure is just formed by two transmission lines arranged in parallel and four resistors. Due to the simplicity of the proposed topology, closed-form expressions have been obtained for the GD at the design frequency and for the maximum attenuation, which allows, under some GD specifications, an easy and fast design. For verification purposes, a prototype has been designed and implemented at 1 GHz to show a very broad negative group delay bandwidth, along with moderate values of NGD and attenuation. The suggested prototype has been also exposed to a communication system environment, where its NGD characteristics has been confirmed. Some future lines have been also discussed.

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