ON THE PERFORMANCE OF NEGATIVE IMPEDANCE CONVERTERS (NICS) TO ACHIEVE ACTIVE METAMATERIALS

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Abstract

One of the main drawbacks when designing microwave circuits or antennas based on metamaterial particles is its inherent low bandwidth and not very good efficiency. An attempt to overcome this problem is based on using negative impedance converters (NICs). Although the use of NICs have been proposed as a solution to increase the bandwidth of electrically small antennas, they suffer from many problems such as stability performance, bias and the maximum frequency that can be achieved. In addition, the application of NICs has been restricted to low frequency applications in order to avoid the previous problems. This paper makes a study on the performance of NICs for active metamaterial applications. The main contributions of the present paper is that it takes into account the non-linear equivalent circuit of the NICs to find out its performance for active metamaterial applications. From that study it can be concluded that NICs can work up to a few GHz.

1. INTRODUCTION

During the last years, the use of the unique properties of metamaterials and the corresponding CRLH transmission lines has opened new possibilities in the design of microwave circuits and antennas. It can be summarized that the additional value that metamaterial cells have provided to microwave circuits or antennas aims at achieving multifrequency and/or miniaturization performance. Many examples can be cited in the previous lines. Then, in [1]-[2] CRLH (composite right-left handed) lines are used to achieve passive microwave circuits with dual-band operation at two arbitrary frequencies; in [3] multifrequency printed antennas were presented by inserting metamaterial particles into conventional patch antennas to achieve multifrequency and miniaturized printed antennas; in [4] an electrically small antenna with a good efficiency was achieved by including μ-negative particles at the back part of a small monopole. The previous four papers are just a sample of the numerous references available in literature related to the great number of circuits and antennas based on metamaterial theory.

However, all the previous contributions suffer from a common problem such as its low operation bandwidth. This drawback is inherent to the Q associated to the metamaterial particles inserted in the transmission lines to make the so called CRLH lines. Several attempts have been undertaken in order to overcome the previous drawbacks and increase both the bandwidth and the efficiency of those circuits and antennas based on CRLH lines. In a first discussion concerning this topic, in [5] it was stated that it was not possible to realize media with real and negative values of the permittivity and permeability with passive linear inclusions. This restriction can be overcome if active inclusions were used instead of passive ones. Although from a theoretical point of view this statement is valid, from a practical point of view the difficulties that arise when using active particles to constitute active metamaterials are very large: stability, bias and maximum frequency that can be achieved, to mention some of them.

Then, two lines of work have been followed in order to tackle with the previous goals. First, the inclusion of tuned elements (i.e. varicaps) in the corresponding CRLH lines has allowed achieving a tunable broad bandwidth for small wire antenna over a ground plane [6]. However, this tunable broad bandwidth is composed of multiple narrow bands associated to the corresponding value of the varicap. It cannot be strictly said that a broad bandwidth has been achieved with this option. Secondly, it is well known from the mid fifties that the so called non-Foster forms [7] employs active networks of negative inductors and capacitors (negative impedance converters, NICS) to bypass the restrictions of gain-bandwidth theory. The idea to be applied in CRLH lines is that conventional LH lines yield to narrow band performance (see left part of Fig. 1) while replacing the LH inductor with an equivalent negative capacitance can yield to broad band performance (see right part of Fig. 1).

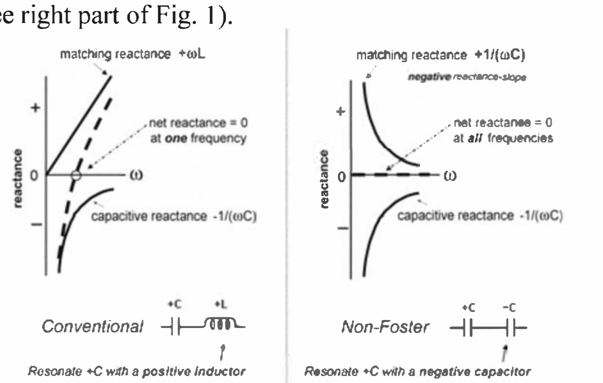


Fig. 1: Performance of a conventional LC circuit vs. a non-Foster form.

Recently in [8] the NICs were applied to match electrically small antennas. They showed up to 20 dB improvement in the corresponding signal to noise ratio (SNR) at 70 MHz band. Their study worked for very low frequencies but when the frequency is increased to higher frequencies large stability problems arise.

This paper presents a study of the performance of the non-Foster forms for its application to the design of active metamaterials. Firstly, ideal models for active and passive elements were applied. Secondly, linear models for the transistors are applied and, finally, a non linear analysis based on the Gummel-Poon model has been applied.

2. NICS MODELLING

An ideal two-port NIC is shown in Fig. 1, where the input impedance, Z_{in} seen at port 1, is the negative (scaled) of the corresponding passive load, Z_L, at port 2. Note that K is the impedance converter coefficient of the NIC in Fig. 2. For the ideal case, K is a positive real constant. However, in an actual NIC, it is not a constant and it is not always real.

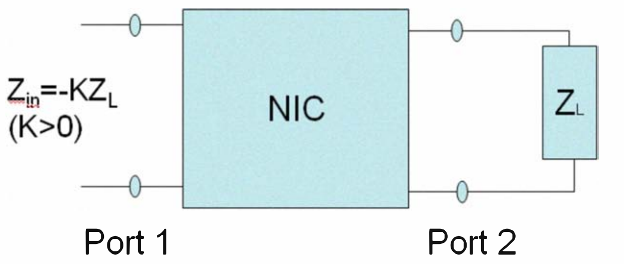


Fig. 2: Overview of an ideal NIC.

Foster's reactance theorem says that the driving-point impedance of a lossless one-port must be a positive-real and odd function of the Laplace-transformed frequency variable. A corollary to this is that the slope of the corresponding reactance-versus-frequency curve is positive. In non-Foster matching, we use lossless impedances that violate the theorem, namely, elements whose reactance-versus-frequency slope is negative. The essential characteristic that makes a non-Foster element so useful is its negative reactance slope.

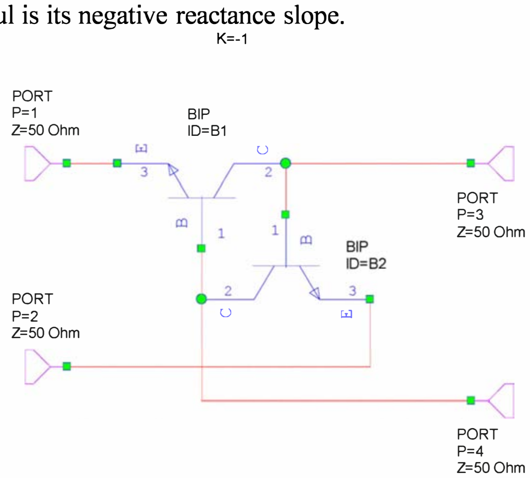


Fig. 3: Overview of an ideal NIC.

Several types of NICs have been published to make impedance inverters [8]. A full study of all of them have been undertaken in order to understand the performance of any of them. Nonetheless due to the finite length of the paper, only the NIC presented in the figure (that is the one that shows better performance in terms of capacitance, inductance and resistance negative conversion) will be studied. The circuits shown is "open-circuit stable" (OCS), meaning, practically, that if a very large resistance terminates the negative-resistance one-ports on the left, then the overall network will be stable.

2.1 Ideal NICs

Initially the proposed impedance inverter is the one shown in Fig. 3 where ideal BJT transistors have been used in order to make the inversion of ideal capacitors, inductors or resistors. The load to be inverted is connected between ports 3 and 4 while port 2 is grounded. The values considered to make the inversion are 150 ohm, 10 nH and 1 pF.

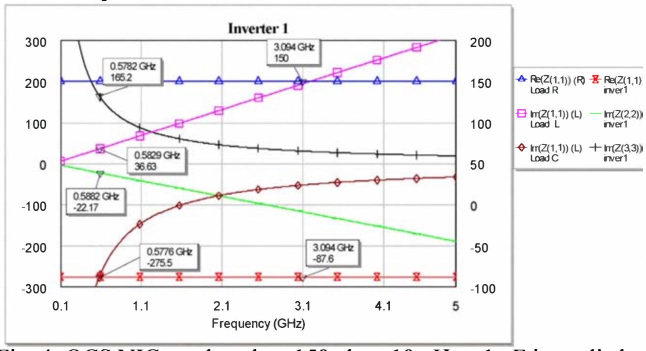


Fig. 4: OCS NIC results when 150 ohm, 10 nH or 1 pF is applied to the output ports.

From Fig. 4 it can be concluded that there is an inversion ratio that is more or less equal for all the load conditions. Then, the corresponding ratio is -0.58 for the resistor, -0.6 for the capacitor and -0.6 for the inductor. We can also see that the performance is valid for a broad margin of frequencies.

When repeating the analysis to all the NICs presented in [7] and [8], it can be concluded that all the NICs do not have the same performance when inverting capacitors, inductors or resistors. Nonetheless, for the ideal case an inversion factor can be defined for any kind of component for most of the cases and for a broad margin of frequencies.

2.2 NICs with real lumped elements (capacitance, inductance and resistance)

The first problem when working with real inverters rises from the fact that the equivalent circuit of the load impedance cannot be modelled as a single element but as a combination of some parasitic elements. The most critical case is the one associated to the resistor that is to be modelled as indicated in **¡Error! No se encuentra el origen de la referencia.**.

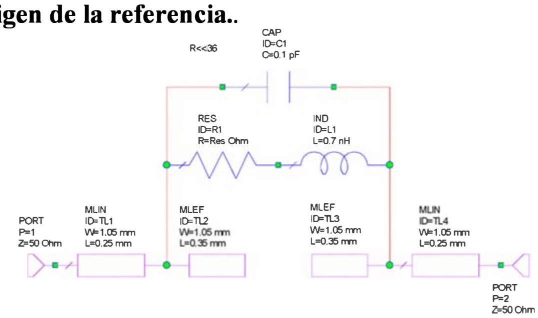


Fig. 5: Equivalent circuit of a real resistor.

It can be seen that the corresponding load has to be modelled with a series parasitic inductance plus a shunted capacitor. In addition two small open transmission lines have to be included to take into account the soldering of the components. The same happens for the inductor and for the capacitor. For this case three different graphs will be shown: one for capacitors, other for inductors and the third one for resistors.

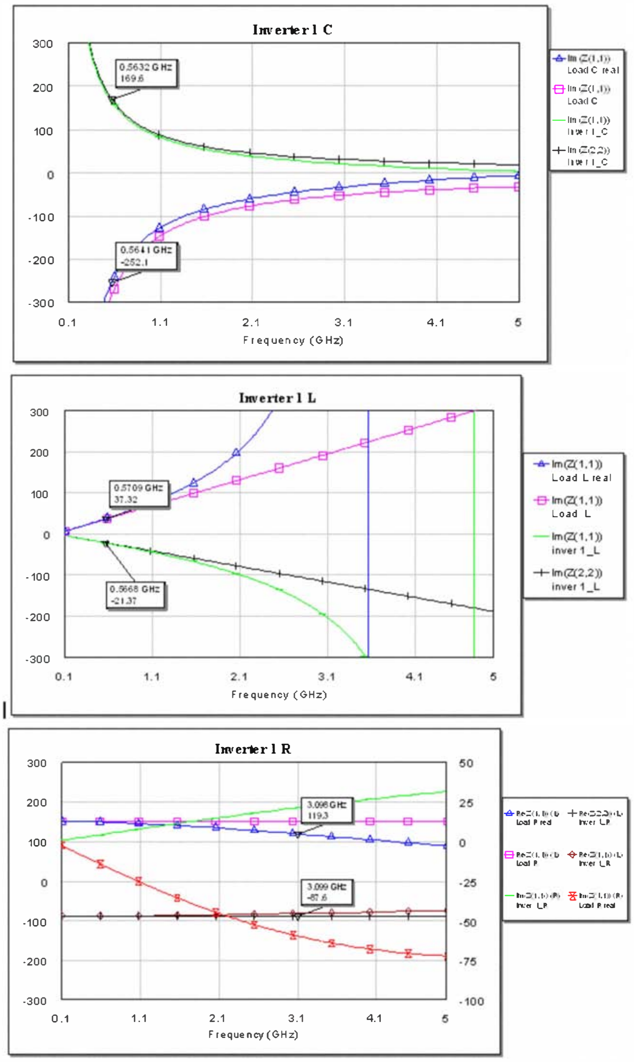


Fig. 6: Output of the inverters for a real capacitance, inductance and resistance.

From the previous figures it can be concluded that the performance of NIC is not the same depending on the load impedance. For this case, the corresponding inverting ratio is not the same, being -0.67 for the capacitor, -0.57 for the inductor and -0.74 for the resistor. In addition, the resistor presents some imaginary parts and the real part is not completely constant due to the inversion of the parasitic effects. Finally, the frequency margin is not the same for all the components. Then, although the capacitor and resistor behaves in a correct way along a broad frequency margin, the inductor presents a cut-off frequency. It can be said that the performance of the inductor is suitable only up to a certain frequency.

2.3 NICs based on a non-linear model

The following model is directly based on a non-linear Gummel-Poon BJT of the corresponding bipolar transistor. This is done in order to take into account the DC-bias and the subsequent variation of the capacitor, inductor and resistor inverted values. Another advantage of the non-linear analysis is the corresponding harmonic analysis.

First the analysis has been undertaken for a BJT transistor due to its simplicity. Fig. 7 shows the non linear model of the BFR193W BJT transistor with all its packaging parasitic elements. These parasitic elements will be the ones that mainly limit the NIC performance. Then Fig. 7 shows the corresponding bonding inductors for any of the ports plus the capacitance between the pad conductors and transistor semiconductor. In addition, the equivalent circuit model of the transistor is hidden in the figure.

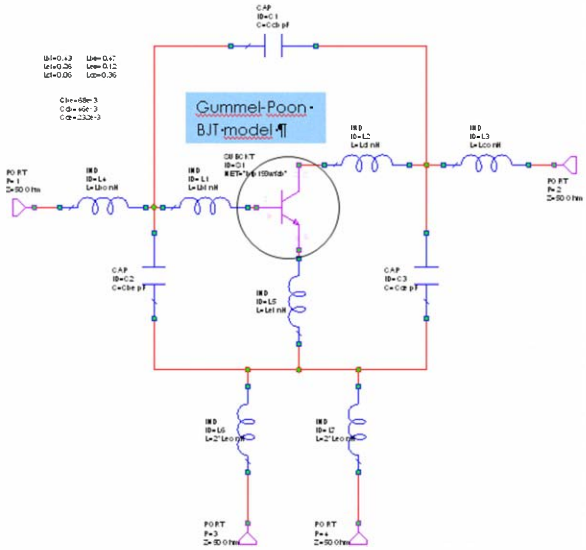


Fig. 7: Non linear Gummel-Poon model with parasitic elements due to package to be used in the NIC design.

It must be emphasized that all the previous elements limit the performance of the NIC at higher frequencies. The NIC to be used at this point is the one in Fig. 3 but changing the transistor by its non linear Gummel-Poon model and the loads by its actual equivalent circuits.

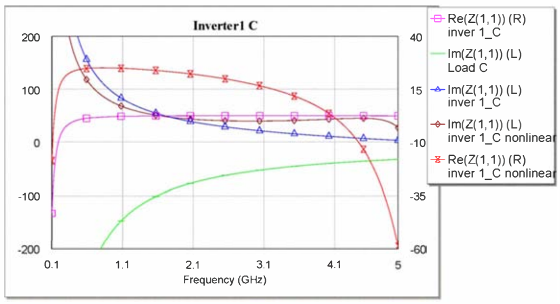
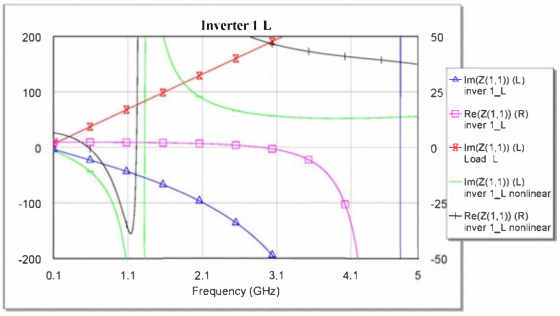


Fig. 8: Inverted capacitance at the output of the NIC

Fig. 8 shows the output of the nonlinear NIC for a real capacitive load. From that figure it can be seen that the inversion affects to either the capacitance and to the parasitic resistance. In addition a comparison with the ideal NIC with an actual load has also been made. The continuous green line represents the actual capacitance to be inverted. The continuous line with Δ is the inverted capacitance through an ideal NIC. The continuous line with ◊ represents the inverted capacitance through the non linear NIC. It can be seen that the performance of the inverter is suitable up to 2.1 GHz where a relative inverted constant value is achieved. It can also be seen that a an inverted resistance appears associated to the parasitic resistance. It must be noted that this resistance is positive due to the presence of the input resistance of the transistor. This effect improves the stability of the NIC at a price of increasing its losses.

The same has been repeated for the inductance and resistance. It can be concluded that the inductors has a limit frequency up to which it can work. For this case it is 1. 1 GHz. The resistance works up to higher frequencies (2.1GHz) but presents an important imaginary part.



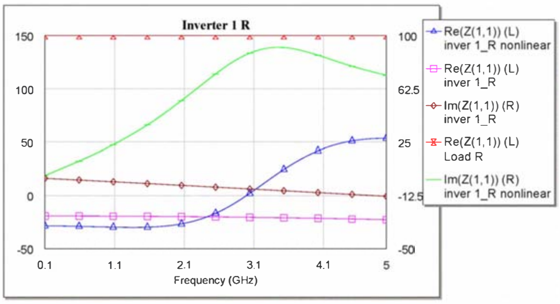


Fig. 9: Inverted inductance (upper figure) and resistance (bottom figure) at the output of the NIC

The corresponding inverting values have been determined for all these elements. Due to the non-linear effects and the parasitic elements it cannot be said that there is a unique inverting value since there are a lot of effects that are not controlled.

3. CONCLUSIONS

The impedance inverter structures can be very interesting for a near future as part of broad band matching networks, as part of broad band metamaterial transmission lines to overcome the traditional drawbacks associated to metamaterials. Their main problems come from their parasitic elements at higher frequencies for the transistor models and from their stability problems. These two facts limit the maximum frequency that can be reached. Using transistors with lower parasitic elements or MMICs can reduce previous problems.

Fourteen potential inverters have been studied but only the most useful has been shown. The agreement between ideal and actual simulations (both with linear S parameter and with non linear parameters following the Gummel-Poon model) can allow a proper design of NICs for its using in small antennas, microwave circuits and broadband metamaterial transmission lines. Up to this point it seems that the performance of negative capacitors and resistors is better than negative inductors.

4. ACKNOWLEDGEMENT

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5. REFERENCES

[1] A. Lai, C. Caloz, and T. Itoh, “Composite right/left-handed transmission line metamaterials“, *IEEE Microwave Magazine*, vol. 5, No. 3, pp. 34-50, September 2004.

[2] I. Lin, M. DeVincentis, C. Caloz, and T. Itoh, “Arbitrary dual-band components using composite right/left-handed transmission lines“, *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 1142-1149, Apr.2004.

[3] F.J. Herraiz-Martínez, L.E. García-Muñoz, V. González-Posadas and D. Segovia-Vargas; “Multi-frequency and dual mode patch antennas partially filled with Left-Handed structures”, *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 8, part 2, pp. 2527-2539, August 2008.

[4] P. Jin, R.W. Ziolkowski; “Low-Q, electrically small, efficient near field resonant parasitic antennas”, *IEEE Transactions on Antennas and Propagation,* vol. 57, no 9, pp. 2548-2565, September 2009.

[5] S. Tretyakov, “Metamaterials with wideband negative permittivity and permeability”, *Microwave and Optical Technology Letters,* vol. 31, no 3, pp. 163-165, November 5, 2001

[6] F.J. Herraiz-Martínez, P.S. Hall, Q. Liu and D. Segovia-Vargas, “Left-Handed Wire Antennas over Ground Plane with Wideband Tuning”, submitted to *IEEE Transactions on Antennas and Propagation*

[7] J. G. Linvill, “Transistor Negative Impedance Converters,” *Proc. IRE*, vol. 41, pp. 725–729, Jun. 1953.

[8] S. E. Sussman-Fort, R. M. Rudish; “Non-Foster impedance matching of electrically-small antennas”, *IEEE Transactions on Antennas and Propagation,* vol. 57, no 8, pp. 2230-2241, August 2009.