Broadband metasurfaces loaded with non-Foster elements

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Abstract. Metasurfaces have been widely used to design low-profile antennas, thin absorbers, lenses etc. The operational frequency band of a metasurface is rather narrow due to its resonant nature. Loading metasurface unit cells with non-Foster elements allows for remarkable bandwidth extension. In this paper, design of a broadband metasurface to operate as an artificial magnetic conductor is considered. The main issues which influence the bandwidth extension such as implementation of the non-Foster load, minimization of conversion error of a negative impedance converter, and circuit stabilization are addressed.

1. Introduction

Non-Foster negative inductances and capacitances have recently attracted great attention due to the unique frequency dependence of reactance or susceptance that cannot be achieved from passive components and is therefore realized by active circuits such as negative impedance converters (NICs). A NIC converts its load impedance into a negative input impedance by flipping the sign of either load voltage or load current. As a result, the NIC input impedance mimics that of a hypothetical passive negative capacitance or inductance. Non-Foster elements (NFEs) are employed for broadband matching of electrically small antennas [1]-[6], to design broadband squint-free leaky-wave and series-fed array antennas [7]-[9], wideband amplifiers [10]-[12], broadband metamaterials [13]-[15] etc.

Metasurfaces are thin periodic two-dimensional artificial structures exhibiting extraordinary reflection or transmission properties [16]. Metasurface applications include low-profile antennas [17]-[20], lenses [21]-[23], thin absorbers [24]-[26] etc. Due to resonant behavior, metasurfaces operate within narrow frequency band. Loading metasurface unit cells with NFEs allows for remarkable bandwidth extension by compensating parasitics or reducing impedance dispersion. Bandwidth enhancement of metasurfaces loaded with NFEs was demonstrated both in simulation and experiment [14], [27]-[31]. The impact of a non-Foster load on bandwidth enhancement of the artificial magnetic conductor (AMC) metasurfaces consisting of an array of metallic patches on top of a dielectric substrate with a ground plane on the bottom was investigated in [14], [27]-[29]. It was shown that any arbitrary operational bandwidth could be achieved in theory with the aid of NFEs [28]. In practice, the bandwidth is limited due to the imperfections of realistic elements which a NIC circuit consists of.

The bandwidth of the AMC loaded with a combination of a negative capacitor and a negative inductor that were realized by Linvill’s circuit NIC was shown to be 30% around the center frequency of 2 GHz, i.e. two-fold wider compared to that of the unloaded metasurface [14]. Different examples of similar non-Foster loaded metasurfaces demonstrate achievement of the operational bandwidth of 56% [29] and 80% [27] while it is limited to 15% in the unloaded case.
In [30], a mushroom-like metasurface loaded with a non-Foster circuit using negative differential resistance characteristic of a graphene-based field-effect transistor was presented. The simulation results revealed an operational bandwidth over 50% at the center frequency of 540 MHz, i.e. enhanced by a factor of 2.4 with respect to the unloaded case.

The concept of using complex non-Foster loads to enhance the bandwidth of a metasurface was also presented in [31]. The metasurface unit cell consists of two orthogonally polarized radiators connected to each other through a NIC. The approach allows for almost perfect compensation resulting in up to 200% bandwidth [31].

In order to design a broadband metasurface loaded with NFEs, implementation of a proper non-Foster load is of crucial importance for obtaining desired performance over a wide frequency band. A single non-Foster reactance or susceptance is frequently used as the load, limiting possibilities for bandwidth enhancement. Moreover, a practical NIC circuit imposes an impedance conversion error due to imperfections of realistic transistors. As a result, the desired negative capacitance or inductance value is realized with some tolerance that limits the metasurface bandwidth as well. The last but not the least, a non-Foster metasurface should be stable for most practical applications although self-oscillating non-Foster metasurfaces can offer new exciting possibilities [31].

In this paper we consider all the three issues: i) implementation of the necessary non-Foster load; ii) minimization of the NIC conversion error; iii) circuit stabilization. We focus on bandwidth extension of an AMC metasurface and demonstrate realization of a non-Foster load with necessary complex frequency dependence of reactance by using a NIC loaded with a circuit consisting of multiple passive components. We illustrate the importance of conversion error minimization. To minimize the NIC conversion error, we employ a design approach based on Linvill’s circuit decomposition, a methodology we have recently introduced [32], [33] as opposed to ‘blind’ CAD optimization that has been commonly used for the NFE design. Besides, we present here for the first time a stabilization technique using high-pass circuits in combination with resistors connected in series.

2. Metasurface design

Fig. 1 shows the well-known mushroom-like structure of AMCs. The unit cell of such a metasurface (Fig. 1-b) consists of a square-shape metal patch and a metallized via hole connecting the center of the patch with a ground plane on the opposite side of the dielectric substrate. The substrate with \( \varepsilon_r = 6 \) and \( h = 2.54 \text{ mm} \) was used. The metasurface designed for the center frequency of 2.45 GHz uses patches of the size \( a = 17.6 \text{ mm} \) separated with the spacing \( s = 1.6 \text{ mm} \). The via hole diameter is \( d_1 = 1 \text{ mm} \).

To load the unit cell with a NFE, a lumped port was implemented by using another metallized via hole of the diameter \( d_2 = 0.254 \text{ mm} \) going from the patch thorough the dielectric substrate. The ground plane metallization around the extra via hole was partially removed forming the circle-shape spacing of the diameter \( d_3 = 2 \text{ mm} \) (Fig. 1-c). The via is positioned 6 mm away from the center of the patch on one of its symmetry axes. Impedance of the lumped port was chosen close to 50 Ohm.

According to results of the full-wave electromagnetic simulations, the metasurface provides full reflection with zero-degree phase at the center frequency (Fig. 1-d). The operational bandwidth measured at ±90° of the reflection coefficient phase does not exceed 7% either with or without the lumped port.

By connecting a proper non-Foster load to the lumped port, the metasurface impedance can be compensated and a broadband operation can be achieved. A necessary impedance which the unit cell should be loaded with (Fig. 2-a), can be calculated from the following equation

\[
Z_l = (Z_{22} Z_{in} - \Delta Z)/(Z_{11} - Z_{in}),
\]

where \( Z_{in} \) is the input impedance of the unit cell with regard to the waveguide port (that should obey the open circuit conditions for the AMC metasurface, i.e. \( \text{Re}(Z_{in}) \gg 377 \text{ Ohm} \) and \( \text{Im}(Z_{in}) = 0 \)); \( \Delta Z = Z_{11} Z_{22} - Z_{12} Z_{21} \) is the determinant of the unit cell impedance matrix; \( Z_{11}, Z_{12}, Z_{21}, \) and \( Z_{22} \) are the impedance matrix elements obtained by the electromagnetic simulation.
Figure 1. A mushroom-like metasurface structure: (a) bird-eye view; (b) unit cell; (c) lumped port to connect non-Foster load; (d) simulated frequency dependence of the reflection coefficient phase.

The simulated frequency dependences of the unit cell input impedance $Z_{in}$ at the waveguide port are shown in Fig. 2-b. In turn, Fig. 2-c presents the necessary frequency-dependent load impedance $Z_L$ at the lumped port that was calculated by (1) in case of $Z_{in} = 20$ kOhm. Obviously, the frequency dependence of $Z_L$ corresponds to a non-Foster load to be implemented with the aid of a NIC. Hence, the unit cell load impedance is equal to the input impedance of the NIC: $Z_L = Z_{NIC}$. To realize such a non-Foster input impedance, the NIC has to be loaded with the impedance $Z_{L,NIC} = -Z_{NIC} = -Z_L$ (see Fig. 2-c). It is also clear that the target frequency characteristic of $Z_{L,NIC}$ cannot be realized with a single reactance/susceptance.

Figure 2. An equivalent diagram of a metasurface unit cell loaded with an impedance $Z_L = Z_{NIC}$ (a), frequency dependence of the real part (solid lines) and imaginary part (dashed lines) of the unit cell input impedance with regard to the waveguide port (b) and the calculated necessary load impedance at the lumped port (c).

To approximate the target frequency characteristics of the NIC load impedance, we employed the RLC-circuit shown in Fig. 3-a. The circuit parameters are $C_S = 0.8$ pF, $C_P = 4.2$ pF, $L_S = 7.8$ nH, $L_P = 1.1$ nH, and $R_P = 28$ kOhm. The approximation accuracy of the circuit is illustrated in Fig. 3-b.
3. Negative impedance converter design

The idealized NIC converts the load impedance into its negative counterpart with the conversion ratio $k = 1$. Due to imperfections of practical NIC circuits, a conversion error is observed in practice. The conversion error affects the tolerance which can be obtained from a NFE within a certain frequency band. Practical NIC circuits are usually optimized numerically to take the conversion error into account.

In [32], [33], we presented a simple and efficient methodology to design NFEs with predictable characteristics, based on Linvill’s NIC employing bipolar junction transistors (BJTs) in the linear mode. The approach uses a decomposition of the NIC into two active and one passive two-port networks, whose frequency characteristics can be analyzed separately and compared with those of their ideal counterparts. The use of the approach simplifies NIC design and allows for conversion error minimization. The approach is much simpler than the direct analysis and optimization of a NIC behavior that is complicated due to sensitive nature of the circuit with positive feedback amplifiers. The obtained results demonstrate a possibility to design broadband NFEs with tolerable variation for GHz range without using any numerical optimization [32], [33].

The same methodology was applied to design the NIC implementing the non-Foster load for the metasurface unit cell. The Linvill’s NIC circuit is presented in Fig. 4-a. A SPICE model of the BFR843EL3 SiGe:C heterojunction BJT by Infineon was employed. The DC biasing voltage was chosen as $U = 12$ V. The biasing resistors $R_1 = 700$ Ohm and DC-decoupling capacitors $C = 10$ nF were used.

As shown in Fig. 4-b, the NIC converts the calculated target impedance $Z_{L,NIC} = -Z_L$ with high degree of accuracy within wide frequency band. Some minor conversion error is observed in the real part of the input impedance $Z_{NIC}$ around the resonance frequency and above 3 GHz. For comparison, Fig. 4-c illustrates the NIC input impedance when using the $RLC$-circuit (Fig. 3-a) to approximate the target impedance $Z_{L,NIC}$. The difference between the target and obtained frequency characteristics is caused by both the NIC conversion error and the approximation inaccuracy of $Z_{L,NIC}$.

The bandwidth of the metasurface unit cell loaded by the NIC with the theoretically calculated load impedance $Z_{L,NIC} = -Z_L$ is greatly improved compared to the unloaded case (Fig. 4-d). The fractional bandwidth of the reflection phase reaches $\Delta f = 53\%$ (dashed line in Fig. 4-d) demonstrating an extension by a factor of 7.6. When the real $RLC$-circuit is used as the NIC load, the bandwidth of the non-Foster loaded metasurface is only extended by a factor of 5.4 and equal to $\Delta f = 38\%$ (solid line in Fig. 4-d).

The NIC conversion error can be further reduced by using transistors with higher critical frequency or composite transistors. The ideal NIC load can be better approximated by employing more elements in the $RLC$-circuit. Besides, a more complex approach to identify necessary NIC load can be used which takes into account the NIC conversion error.

4. Circuit stabilization

NIC circuits are by nature amplifiers with a positive feedback loop and consequently prone to instability. Most practical applications of the non-Foster loaded metasurface require their stable operation.
Figure 4. Linvill’s NIC circuit (a), its input impedance when loaded by the calculated target impedance \( Z_{L,NIC} = -k \cdot Z_L \) (b) and by the real RLC-circuit (c), phase of the reflection coefficient of the unit cell loaded with the NIC (d).

In order to provide stable operation, we introduce a stabilization network in the NIC circuit as shown in Fig. 5-a. The stabilization network consists of a high-pass filter with the parameters \( L_{stab} = 4.3 \) nH and \( C_{stab} = 15.5 \) pF as well as the resistor \( R_{stab} = 670 \) Ohm. The high-pass filter is aimed at elimination of the DC-pole, which causes instability [34]. In turn, the resistor limits the current gain [33].

A combination of the high-pass filter and the current gain limiting resistor which has not been used before according to the authors’ best knowledge, allows obtaining stable operation of the NIC circuit connected to the metasurface unit cell. The stability is proved by either analysis of the normalized determinant function (NDF) [35] behavior (Fig. 5-b) or the simulation of time-domain transient response of the circuit (Fig. 5-c).

Since the stabilization resistors change the NIC input impedance to some extent, the conversion error increases for a NIC with the stabilization networks. This leads to less efficient broadening of the operational bandwidth of the non-Foster loaded metasurface. Nevertheless, the bandwidth enhancement from 7% to 15%, i.e. by a factor of 2.1 was achieved by the results of simulation for the metasurface loaded by the NICs with the stabilization networks (Fig. 5-d). This is the largest increase in the bandwidth that was demonstrated for an AMC metasurface loaded with practical NICs at GHz frequencies.

The NIC performance degradation caused by the presence of stabilization networks can be mitigated by adjusting the NIC circuit parameters. On the other hand, any changes to the NIC circuit might lead to instability that will require to change parameters of the stabilization networks once again. Therefore, an iterative design approach is needed to obtain a stable NIC with suitable frequency characteristics. Furthermore, the approach should also take into account adjustment of the NIC load to compensate for residual conversion error.

5. Conclusion

Due to resonant nature, a metasurface operates within a very limited frequency band. Loading metasurface unit cells with NFEs gives possibilities for broadening the operational bandwidth. Design of a NFE for such purpose deals with implementation of the necessary frequency-dependent non-Foster load, minimization of the NIC conversion error, and circuit stabilization. All of the issues impact a metasurface bandwidth enhancement and were addressed in the paper.
Design of a non-Foster loaded AMC metasurface with the bandwidth extended by a factor of 5.4 when using practical Linvill’s BJT NIC was presented. The wide bandwidth was achieved because of low NIC conversion error and a complex NIC load used. To minimize the conversion error, the NIC was designed by using methodology based on decomposition of Linvill’s circuit.

The stabilization networks consisting of a high-pass filter and a resistor limiting the current gain were presented for the first time. With the aid of such stabilization networks, a stable operation of the non-Foster loaded metasurface was achieved. Presence of the stabilization networks limits possibilities for the metasurface bandwidth enhancement. For a stable metasurface, the bandwidth extension by a factor of 2.1 compared to the unloaded case was demonstrated.

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