

# An Efficient, Electrically Small Antenna with Large Impedance Bandwidth Simultaneously with High Directivity and Large Front-to-Back Ratio

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**Abstract**—Non-Foster element-augmented, electrically small electric and magnetic antennas have been designed, characterized numerically, fabricated and tested. Specifically tailored broad bandwidth inductive and capacitive devices were introduced into the near-field resonant parasitic (NFRP) components of their narrow bandwidth counter-parts. This internal non-Foster element approach led to nearly complete matching of the entire system to a 50  $\Omega$  source without any matching network and high radiation efficiencies over a 10dB fractional bandwidth that surpasses the fundamental passive bound. By including additional resonant parasitic elements, one can also enhance the directivity. Further augmentation of those parasitic elements with a non-Foster device leads to a large directivity bandwidth. A 300 MHz design with  $ka = 0.94$  is reported which simultaneously achieves high radiation efficiencies (>81.63%), high directivity (> 6.25 dB) and large front-to-back-ratios (> 26.71 dB) over a 10.0% fractional bandwidth.

## I. INTRODUCTION

Electrically small antennas (ESAs) continue to be a topic of great research and practical interest because of their utility for a wide variety of wireless applications. Because of their compact size, passive ESAs are generally not efficient radiators and they have narrow bandwidths. There have been many efforts to overcome the conflicting performance characteristics of ESAs. This includes their efficiencies, bandwidths, and directivities. Successful miniaturized antenna designs have been reported recently based on some type of meta-structure (see, e.g., [1] and the references therein). By introducing a negative impedance convertor (NIC) based reactive element into the near field resonant parasitic (NFRP) element of these metamaterial-inspired ESAs, it was demonstrated [2] that frequency bandwidths can be obtained which are substantially larger than the known fundamental passive upper bounds based on the electrical size of the antenna. We note that throughout, the term "electrically small" will mean:  $ka < 1$ , where  $k = 2\pi / \lambda_r$ ,  $\lambda_r$  being the free space wavelength corresponding to the resonance frequency,  $f_r$ ,

of the entire antenna system, and  $a$  is the radius of the smallest sphere that encloses it.

## II. NON-FOSTER IMPEDANCE MATCHING BANDWIDTH ENHANCEMENT

We have designed, simulated, fabricated and tested two NIC-augmented antenna types [3], [4]. The process involves selecting a passive NFRP ESA whose bandwidth is near the fundamental passive limit and whose NFRP element can be modified to allow for the introduction of a reactive element to achieve the same resonance frequency with only minor, if any, performance characteristic variations. A frequency dependent version of the reactive element is then introduced. The resulting frequency agile version of the antenna is then simulated with an electromagnetic solver, such as the ANSYS-ANSOFT high structure frequency simulator (HFSS). The resonance frequencies corresponding to the various values of that reactive element are thus obtained, and the corresponding reactance versus frequency curve is determined. A NIC-element is then designed with a circuit simulator, e.g., Agilent's Advanced Design System (ADS), to match this curve as closely as possible. Since realistic values of the lumped elements and transistors are incorporated in the NIC model, it will produce not only the desired reactance values, but also resistances. These resistances have to be minimized to maintain the desired high radiation efficiencies. This is accomplished by optimizing the various circuit components in the NIC elements. The resulting NIC-element values are co-simulated with the antenna model to ensure that the design will produce the desired performance characteristics: impedance matching, radiation efficiency, directivity and front-to-back ratio, over the enhanced frequency bandwidth.

The first successful realization of an efficient, broad impedance bandwidth ESA was the protractor antenna [3]. In this system, a coaxially-driven monopole is coupled to a protractor NFRP element in such a manner that the current induced in it is a loop mode. Thus it acts as an elemental

magnetic dipole antenna. A frequency agile version is obtained by introducing a capacitor across the gap of the protractor element. Then, to achieve a large instantaneous bandwidth, a capacitive NIC (C-NIC) element was designed to match the frequency agile capacitor behavior. It was then introduced into the protractor NFRP element and the complete system was optimized. This C-NIC augmented protractor antenna was experimentally validated [3]. Comparisons of the simulated and measured results were demonstrated to be in reasonable agreement [3].

The second successful realization of an efficient, broad impedance bandwidth ESA was the Egyptian axe dipole (EAD) antenna [4]. In this system, a coaxially-driven top hat loaded printed dipole is capacitively coupled to a printed EAD NFRP element. At resonance, the current flows mainly along the handle of the NFRP EAD element. Thus, it acts as an elemental electric dipole antenna. A frequency agile version is obtained by introducing a gap in that handle and then reconnecting the resulting two pieces of the handle with an inductor. Next, to achieve a large instantaneous bandwidth, an inductive NIC (L-NIC) was designed to match the frequency agile capacitor behaviour. It was then introduced into the EAD NFRP element and the complete system was optimized. The resulting L-NIC augmented EAD antenna was fabricated and experimentally validated [4]. Comparisons of the simulated and measured results were demonstrated to be in reasonable agreement [4].

Both designs, emphasizing their physics and engineering, will be briefly reviewed in the presentation. This discussion will include issues related to the passive system; the NIC-augmentation process; and the design, simulation, fabrication and testing of the active system.

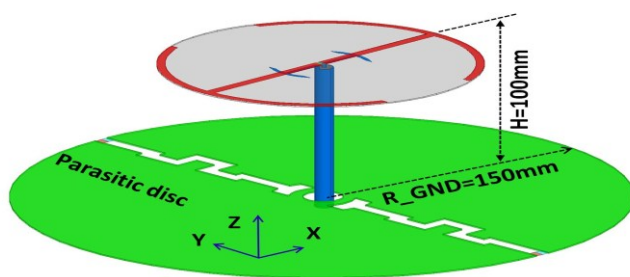


Fig.1. 3D isometric view of the coaxially-fed EAD antenna integrated with a slot modified parasitic disk. The EAD is augmented with an L-NIC to enhance its impedance bandwidth. Two C-NICs are introduced across the end gap regions of the slots in the parasitic disk to increase its directivity bandwidth. [6]

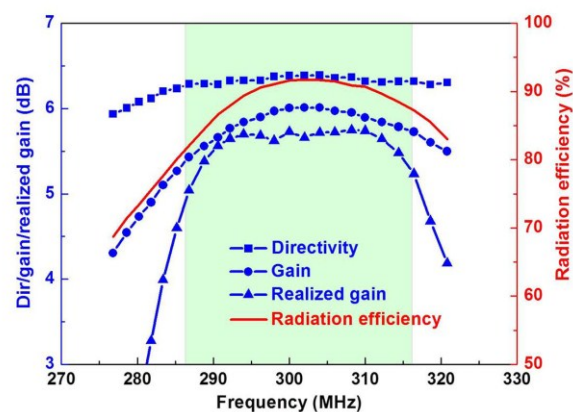
### III. NON-FOSTER DIRECTIVITY BANDWIDTH ENHANCEMENT

Because the protractor and EAD antennas are electrically small, they operate intrinsically in their fundamental dipole

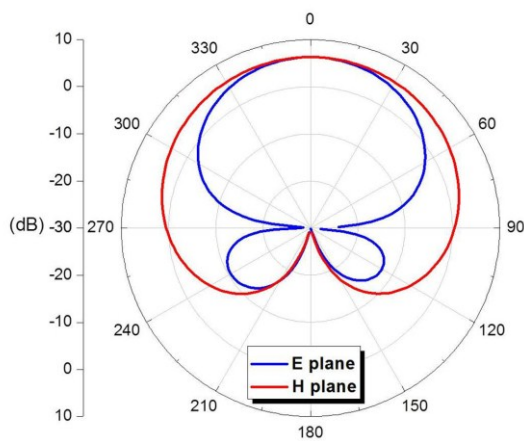
modes. As a result, the corresponding directivities are relatively low (about 1.76 dB). However, we have found that by integrating a slot-modified parasitic disk with the non-augmented EAD antenna in its near field, as shown in Fig.1, one can control the relative amplitudes and phases of the currents on the NFRP element of the EAD and on the disk to achieve higher directivity and a large front-to-back ratio (FTBR) [5]. Furthermore, by introducing C-NICs into the ends of the slots of this resonant parasitic element, one can increase the bandwidth of this directivity enhanced system. It will be shown that a  $ka = 0.94$  system can achieve directivities from 5.66–6.34 dB with FTBR values all greater than 20 dB and a radiation efficiency greater than 65.2% within a 41.1 MHz bandwidth from 281.2 to 322.3 MHz [5].

### IV. FULLY NIC-AUGMENTED ESA

It has also been demonstrated that one can simultaneously augment the EAD antenna system with an L-NIC to enhance its matching bandwidth and then additionally augment its slot-modified parasitic disk with C-NICs to enhance its directivity bandwidth [6]. It will be demonstrated that one can achieve in this manner simultaneously nearly complete impedance matching to the source, high efficiency, high directivity and a large FTBR with an electrically small system. In particular, it will be shown [6] that with a 300 MHz,  $ka = 0.94$  design, one can simultaneously achieve high radiation efficiencies ( $>81.63\%$ ), high directivity ( $> 6.25$  dB) and large front-to-back-ratios ( $> 26.71$  dB) over a 10.0% fractional bandwidth. These performance characteristics are shown in Figs. 2(a). The corresponding E- and H-plane directivity patterns at 300 MHz are given in Fig. 2(b). These results demonstrate that designs can be achieved that overcome the usual trade-offs associated with ESAs and even the fundamental physics limits for the performance characteristics of passive electrically small antennas.



(a)



(b)

Fig.4. Fully non-Foster augmented, EAD-based, electrically small antenna system. (a) Simulated directivity, realized gain, and radiation efficiency values versus the resonance frequency. The cyan shaded region represents, for easy reference, the instantaneous 10 dB frequency bandwidth,  $BW_{10dB}$ , region. (b) E- and H-plane directivity patterns at  $f_r = 300$  MHz [6].

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