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*DOI:*
10.1109/LAWP.2012.2199460

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*Document Version*
Peer reviewed version

*Citation for published version (Harvard):*
Kokkinos, T & Feresidis, AP 2012, 'Electrically small superdirective endfire arrays of metamaterial-inspired low-profile monopoles', *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 568-571. https://doi.org/10.1109/LAWP.2012.2199460

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# Electrically Small Superdirective Endfire Arrays of Metamaterial-Inspired Low-Profile Monopoles

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*Abstract*— **This paper presents the design and experimental characterization of subwavelength, superdirective, endfire antenna arrays operating in the 2.45 GHz band. Microstrip-fed, low-profile folded monopoles are designed using metamaterial-inspired phase-shifting lines composed of inductively coupled spiral resonators and employed for the synthesis of three different superdirective, two-element antenna arrays with variable inter-element spacing. High directivity values are obtained experimentally. The experimental results show that the radiation efficiency of the reported arrays decreases as the inter-element spacing of the arrays is reduced. Nevertheless, the directivity increase that is achieved with the inter-element spacing reduction compensates the efficiency reduction, enabling even the more compact arrays to deliver reasonable gain values.**

*Index Terms*— **Superdirective antennas, phased arrays, 1-D metamaterials, monopoles.**

## I. INTRODUCTION

Superdirective arrays have attracted for years the interest of antenna engineers both from theoretical (conceptual) and practical point of view [1], [2]. For the case of endfire superdirective arrays composed of N isotropic and uncoupled radiators, it has been shown in [3] that as the element spacing approaches zero, the upper limit for the delivered directivity converges to $N^2$. This maximum directivity value can be achieved only if the elements of the array are properly excited [2], [3]. Nevertheless, in practice, the theoretical upper limit of the endfire directivity is difficult to be achieved as the performance of superdirective arrays is prone even to minor divergences between the theoretical and the experimental excitation signals of the individual array elements. Furthermore, the strong coupling between the individual radiators of the subwavelength arrays tends to further reduce their experimental performance.

Despite the difficulties associated with the experimental demonstration of superdirectivity, there have been several recent references in the literature that report measured superdirective radiation performances. For example, in [2] a two-element superdirective endfire array is reported, in which a tunable feeding network is incorporated to fix dynamically the required excitation currents of the individual elements of the array and alleviate the impact of the coupling. A similar approach was employed in [4], in which electrically small radiators were employed. In [5], broadside superdirective radiation patterns were measured for a compact five-element compact patch array in which metamaterial-based insulators had been used of the reduction of the coupling between adjacent elements. Finally, compact high-gain metamaterial-based patch antennas with end-fire radiation at specific frequencies have been presented recently [6]. However, these are electrically larger and are not based on superdirective antenna design concepts.

In this work, a new approach is employed for the synthesis of electrically small, superdirective, endfire two-element arrays. The proposed method eliminates the need for tunable feeding networks or additional insulators between the radiating elements. In particular, metamaterial-inspired, microstrip-fed, low-profile folded monopoles (LPFM), that exhibit improved coupling performance as compared to conventional λ/4 monopoles and are much more robust to any detuning in the presence of high mutual impedances, are incorporated together with single-port, static, microstrip-based feeding networks for the synthesis of the aforementioned arrays. The experimental results show that superdirective patterns can be measured in the 2.45 GHz band even for such simple and low-cost antenna arrays.

This paper, that comprises a more inclusive version of the work presented in [7], is structured as follows. In Section II, the microstrip-fed, low-profile, folded monopole that is employed for the synthesis of the reported arrays is presented and it is shown how the performance of this radiator when used to form compact arrays ($d<0.2\lambda$) enables the synthesis of single-port superdirective arrays. In Section III, the feeding network that is used for the synthesis of these arrays is explicitly presented, together with the measured performances of three different superdirective arrays with variable inter-element separation (0.2λ, 0.15λ and 0.1λ, respectively). Finally, in Section IV, the performances of these three arrays are compared and the results are discussed.

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Manuscript submitted on October 15, 2011. This work has been partially supported by EPSRC through a fellowship for doctorate studies.

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## II. MICROSTRIP-FED LOW-PROFILE FOLDED MONOPOLES

### A. *Single Element Design and Measured Performance*

The constitutive element of the reported arrays is a microstrip-fed, low-profile folded monopole (LPFM), which is composed of two short vertical radiating wires, loaded with a pair of non-radiating, inductively coupled spiral resonators that form a metamaterial-inspired phase-shifting line and set the self-resonance of the entire structure. This type of antennas, fed through a coaxial configuration, has been explicitly presented in [8]. The schematic of this antenna is shown in Fig. 1. For the purposes of this study, the total footprint of the LPFM has been $d_1$ x $d_2$ =12.1 mm x 3.8mm, while the total profile of the LPFM is $h_{total} = h + 2h_{sub} = 10.3$ mm, where $h_{sub}$=1.15mm is the thickness of the dielectric substrate on which the spiral-based phase-shifting lines (top substrate) and the antenna ground plane (bottom substrate) have been etched. The ground plane size has been 60mm x 60mm. The phase-shifting line has been designed so as the LPFM antenna achieves its self-resonance around 2.45 GHz. At this frequency, its total profile corresponds to approximately $\lambda/12$ and the ground plane size corresponds to $\lambda/2$ x $\lambda/2$.

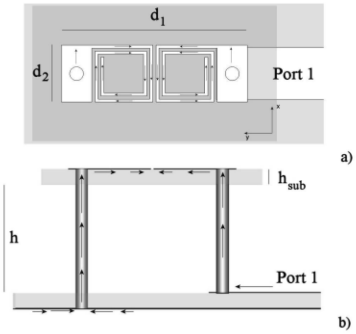


Fig. 1. a) Top-view and b) side-view schematic representation of the microstrip-fed, low-profile, folded monopole used for the synthesis of the superdirective, endfire arrays.

In Fig. 2, the simulated and measured return loss of the LPFM of Fig. 1 is presented. The slight discrepancy between these results is attributed to manufacturing inaccuracies (extra capacitance due to the soldering of the radiating wires on the feeding and the phase-shifting lines). In Fig. 3, the measured E- and H-planes of the $\lambda/12$ LPFM of Fig. 1 are depicted. The asymmetry of the E-plane and the two nulls that appear on the H-plane are both attributed to the SMA connector that is connected to the microstrip line that feeds the LPFM. The directivity of this antenna has been measured to be 3.1 dBi and its radiation efficiency has been estimated to be 43% (through the Directivity/Gain comparison method).

### B. *Mutual Coupling Assessment*

The performance of the LPFM of [8] and of Fig. 1 is significantly less sensitive to mutual coupling when used to form compact antenna arrays, as compared to conventional $\lambda/4$ monopoles. It has been established through multiple simulations that between closely spaced $\lambda/12$ LPFM the supported coupling is on average 4 dB less than that between conventional $\lambda/4$ monopoles. Furthermore, the mutual impedances between LPFM do not appear to have any major impact on the tuning of the individual elements. This is due to the fact that the resonance of each LPFM is mainly enforced by its phase-shifting line, which is not affected by the mutual coupling (non-radiating part of the LPFM). These observations are depicted in Fig. 4, in which the simulated S-parameters for pairs of $\lambda/4$ monopoles and $\lambda/12$ LPFM being 0.15λ apart are presented. As it is clearly depicted, between the $\lambda/4$ monopoles a coupling of approximately -6.5 dB is supported, and this coupling detunes the return loss of the individual monopoles. On the contrary, for the case of the $\lambda/12$ LPFM, the coupling is at -10 dB and their return loss appears to be unaffected.

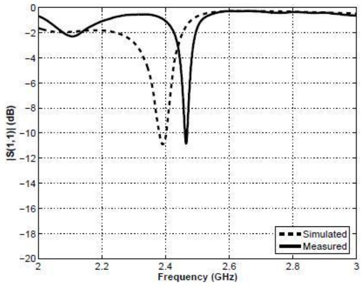
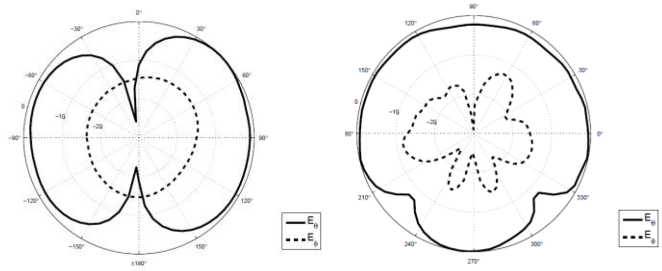


Fig. 2. Simulated and measured return loss of the $\lambda/12$ LPFM of Fig. 1.



a) b)

Fig. 3. Measured a) E-plane (yz-plane) and b) H-plane (xy-plane) radiation patterns of the $\lambda/12$ LPFM Fig. 1 (measured at 2.47 GHz). In the E-plane pattern, the SMA connector that feeds the antenna is located at 90°, while in the H-plane is located at 270°.

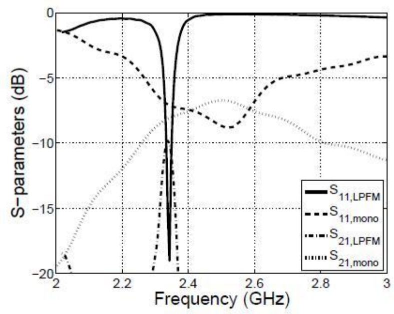


Fig. 4. Simulated S-parameters for pairs of $\lambda/4$ monopoles and $\lambda/12$ LPFM being 18 mm apart.

## III. SUPERDIRECTIVE ARRAYS

### *A. Feeding Network and Array Layout*

Given the robustness of the LPFM to mutual coupling, it is suggested that they could be employed together with low-cost, static feeding networks to form sub-wavelength arrays and deliver endfire superdirective patterns according to the theory of [2] and [3]. Specifically, according to theory of [2] and [3], superdirective endfire patterns can be delivered by sub-wavelength, two-element arrays when they are fed with currents of equal magnitude and relative phase that depends on the spacing between them. The function of that relative phase with respect to the spacing between the array elements is shown in Fig. 5.

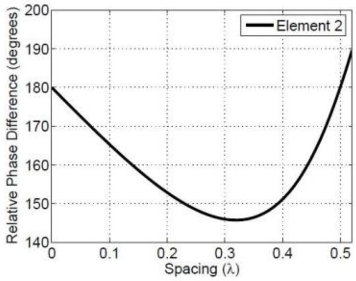


Fig. 5. Phase difference between the excitation signals for two-element endfire superdirective arrays as a function of the inter-element spacing, according to the theory of [2] and [3].

Given that the phase differences shown in Fig. 5 are in the region of 180°, it is proposed that an extremely simple feeding network that could implement instances of this function is the one depicted in Fig. 6. This feeding network is mainly composed of a microstrip-based rat race coupler. At the out-of-phase ports of the coupler, microstrip transmission line segments of lengths $l_1$ and $l_2$ are employed to fix the distance between the array elements d, and also the phase difference with which the two antenna elements will be fed (any phase difference-spacing pairs are set according to Fig. 5). Then the LPFM can be connected at the open ends of the aforementioned transmission lines, as also depicted in Fig. 6.

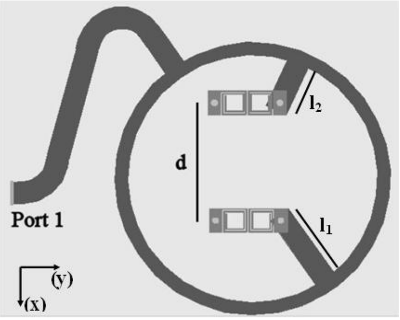


Fig. 6. Top-view of the proposed microstrip-based, two-element, endfire superdirective arrays. The feeding network is implemented using a rat race coupler and transmission line segments of proper length connected at the out-of-phase ports of the coupler.

### *B. Driven 0.2λ Array*

Based on the feeding network of Fig. 6, the first sub-wavelength array that is prototyped is a two-element driven array with inter-element spacing of 0.2λ (at 2.45 GHz). For the design of this antenna, the lengths $l_1$ and $l_2$ have been set to maintain a separation of d=24mm between their open ends, and also a phase difference of 155°, as suggested by Fig. 5. A photograph of the manufactured prototype is depicted in Fig. 7. The material that was used for the implementation of the feeding network was the TACONIC TLY-5A, 1.15mm thick substrate. The total size of the antenna ground plane is 60mm x 60mm, identical with that of the single microstrip-fed LPFM. The measured return loss and the H-plane of this array are reported in Fig. 8. These results suggest that the antenna is matched at -6 dB over a bandwidth of 35 MHz around 2.48GHz, the directivity of this antenna is 5.7 dBi and its radiation efficiency 40% (estimated using the Directivity/Gain comparison method). An additional resonance that appears at about 2.05 GHz corresponds to a non-radiating mode supported by each folded monopole.

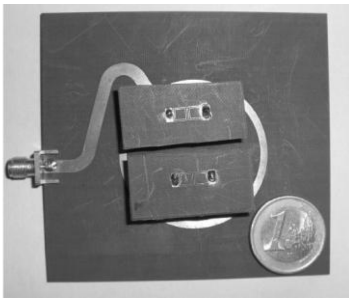
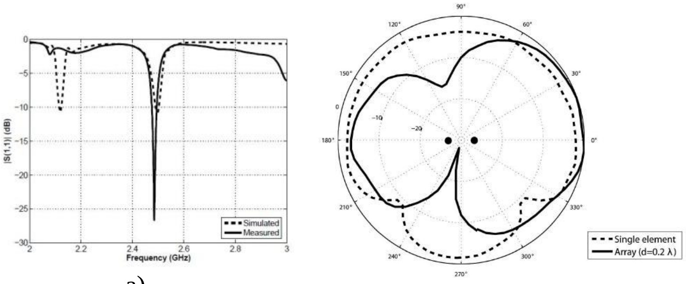


Fig. 7. Photograph of one of the manufactured prototypes. For this prototype, the inter-element spacing is d=24mm (0.2λ at 2.45 GHz).



a)

b)

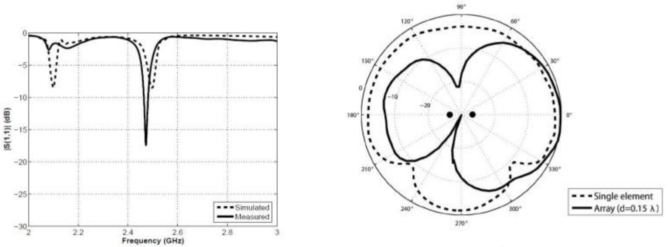
Fig. 8. a) Measured and simulated return loss and b) measured (at 2.475 GHz) H-plane radiation pattern of the two-element driven array when the inter-element separation is d=0.2λ. The H-plane pattern at 2.47 GHz of the single element is also shown as reference. The two dots represent the relative position of the array elements.

### *C. Driven 0.15λ Array*

The second array that has been prototyped is again based on the layout of Fig. 6, but, as compared to the array of Fig. 7, the inter-element spacing has been set to be d=18 mm (0.15λ at 2.45 GHz). The measured performance of this array is presented in Fig. 9. According to these results, the 0.15λ array is matched at -6 dB over a bandwidth of 30 MHz around 2.475 GHz. The directivity of this array has been measured at 6.9 dBi, and its radiation efficiency at 30%.

### D. *Parasitic 0.1λ Array*

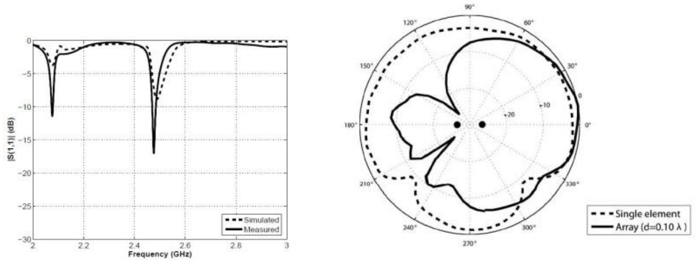
The feeding network of Fig. 6 becomes slightly impractical for sub-wavelength arrays with inter-element spacing below 15 mm. For this reason, the last sub-wavelength array that has been prototyped is a parasitic two-element array with d=12mm inter-element separation (0.1λ at 2.45 GHz). For this configuration, one of the array elements has been fed using a microstrip line (driven element), while the second element, being 12 mm apart, has been a shorted LPFM (parasitic element, reflector). A similar configuration has been also investigated in [9]. For inter-element distances below 0.1λ, such configurations satisfy well the phase-spacing constraint of Fig. 5, given that the parasitic element is excited out-of-phase from the driven element.



a) b)

Fig. 9. a) Measured and simulated return loss of the two-element driven array (inter-element separation: 0.15 λ) and b) measured (at 2.475 GHz) H-plane radiation pattern of the two-element driven array when the inter-element separation is d=0.15λ. The H-plane pattern at 2.47 GHz of the single element is also shown as reference. The two dots represent the relative position of the array elements.

The measured results of this array are presented in Fig. 10. The parasitic array remains matched at -6 dB over a bandwidth of 25 MHz around 2.475 GHz, while its directivity was measured to be 7.6 dBi and its radiation efficiency 24%.



a) b)

Fig. 10 a) Measured and simulated return loss of the two-element parasitic array (inter-element separation: 0.10 λ), and b) measured (at 2.475 GHz) H-plane radiation pattern of the two-element parasitic array (the inter-element separation is d=0.10λ). The H-plane pattern at 2.47 GHz of the single element is also shown as reference. The two dots represent the relative position of the array elements.

## IV. ARRAYS COMPARISON AND DISCUSSION

The measured radiation properties (directivity, gain, and radiation efficiency) of the arrays reported in Section III are summarized in Table I. These results suggest that the two-element arrays directivities are from 2.6 dB to 4.5 dB larger than that of the single element. Although larger directivity values have been reported in the past for two-element endfire arrays (e.g. in [2]), in this work such directivity values are obtained from low-profile arrays fed by single port, low-cost, static feeding networks. Even though the actual gains of these arrays are relatively low (1.7, 1.6, and 1.4 dBi respectively), as was expected given the theory of [2] and [3], they are still interestingly high, given that they have been derived from antennas of a total volume of approximately λ/11 x λ/ 7 x λ/12 (such is the volume of the 0.15λ array), excluding the ground plane size. Such antennas can be extremely attractive within the context of interference limited systems, such as WLAN access points or other small cell applications, in which the antenna directivity is more critical than its actual gain.

TABLE I
DIRECTIVITY, GAIN AND RADIATION EFFICIENCY COMPARISON FOR THE THREE REPORTED ARRAYS

| Antenna Description | Directivity (dBi) | Gain (dBi) | Radiation Efficiency (%) |
|---|---|---|---|
| Single Element | 3.1 | -0.5 | 43 |
| Driven 0.2 λ Array | 5.7 | 1.7 | 40 |
| Driven 0.15λ Array | 6.9 | 1.6 | 30 |
| Parasitic 0.1λ Array | 7.6 | 1.4 | 24 |

## ACKNOWLEDGMENT

The authors would like to thank Mr Thomas Rufete-Martinez for his help on the design of the feeding networks and the processing of the measured results. We also thank CST for providing licenses for CST Microwave Studio$^{TM}$.

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