13th International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials 2019
Rome, Italy, Sept. 16th – Sept. 21st, 2019

Superdirective Antennas of Coupled Helical Elements

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***Abstract* – Using magnetically-coupled structures formed of subwavelength metallic helices, we demonstrate superdirective end-fire radiation in the low GHz frequency range. Numerical, experimental and analytical results are presented on superdirective dimers that are almost three times smaller compared to previously demonstrated dimers of split-ring-resonators (0.09λ compared with 0.25λ). Optimisation of such structures in terms of their size, directivity, efficiency and operational passband is demonstrated.**

I. INTRODUCTION

The concept of superdirectivity was first proposed by Oseen almost a century ago [1]. Unlike conventional phased arrays that provide high directivity by means of constructive interference, the superdirective antennas are based on destructive interference that suppresses radiation in all directions, however for the direction of the main lobe the destructive interference is a minimum and hence the radiation there is a relative maximum. Broad theoretical research has been conducted throughout the century [2-4] that resulted in a mathematical procedure for finding the maximum directivity for a given arbitrary array of radiating dipoles. As theoretically shown by Solymar [5], to achieve the highest values of directivity, the fields in the system should exhibit strong spatial variations at distances shorter than the free-space wavelength. To achieve this, the amplitude and phase of the current in each element of the array must be controlled precisely, which is difficult to realise experimentally. Some practical solutions have been suggested [6,7] but no general approach has been proposed.

A fresh way to realise superdirectivity appeared with the emergence of metamaterials with studies on magnetoinductive (MI) waves [8,9] showing that coupling between the elements in a metamaterial can provide strong spatial variations of fields at distances shorter than the free-space wavelength. The first attempts to utilise metamaterials for superdirective antennas appear to be those of Buell [10] and Yaghjian [11,12], that were further developed by S. Lim, and H. Ling [13].

Finally in 2013 researcher proposed superdirective arrays with one element fed and others left open [14,15]. It was predicted theoretically [4, 16] that a far-field superdirectivity with a maximum value of directivity $D = 5.25$ is possible in structures composed of two coupled split ring resonators (SRRs) when their size and the distance between them both tend to zero. The required phase difference between the currents in the resonators and their magnitudes provide the strong negative magnetic coupling between them [17]. High values of D were shown for both MHz [18, 19] and GHz [20] frequency ranges using dimers formed of two coplanar split ring resonators (SRRs), with the first being driven and the second passively excited. It was theoretically demonstrated [14, 19] that the directivity of such a structure depends on several parameters: the coupling coefficient, κ, the centre-to-centre distance, a, the operating wavenumber, k, and the quality factor, Q. To achieve the theoretical maximum value of directivity, the following relation between them need be satisfied,

$$\frac{Q|\kappa|}{\sqrt{1-\kappa/2}} = \alpha \frac{5}{ka}, \tag{1}$$

where α is a dimensionless parameter that depends on the geometry of the elements.

In this present work, we propose an alternative element geometry: a metal helix in the normal mode of radiation. It demonstrates benefits both in terms of size reduction and improved directivity of the superdirective dimer structure when compared to the previous work using SRRs. The radiation properties of the helical dimer structures are analysed for different frequencies and element configurations using numerical modelling, analytical calculations end experimental measurements.

II. EXPERIMENTAL SET-UP

The experimental set-up of the superdirective dimer of helices is presented on Fig. 1. The helices are supported on a 3D-printed platform of Ultimaker black PLA ($\varepsilon = 2.6 + 0.04i$). The base is constructed so that the distance between the element centres can be freely changed from $a = 3$ to 35 mm allowing one to readily satisfy the superdirective condition (1). Helices are made from copper wire with wire radius $r = 0.1$ mm. The first helix is fed inductively via a concentrically placed single copper loop soldered to a semi-rigid coax cable. As the loop itself has much higher resonant frequency then the helix, it does not radiate much power at the operational frequency, and thus does not interfere with the far field pattern of the dimer. However the helical resonator geometry makes it possible to achieve high power transfer from the loop to the first helix; 78% at the frequency of maximum directivity. A schematic representation of the helices is presented in Fig. 2. The proximity of the feeding loop perturbs the frequency of the first helix, and therefore we adjust the number of turns and height of the 2nd helix so that their frequencies are matched ($f_0 = 1.53$ GHz).

Fig.1. Experimental setup of superdirective dimer. Copper helices are wired around PLA base ($\varepsilon = 2.6$). Resonant frequency $f_0 = 1.53$.

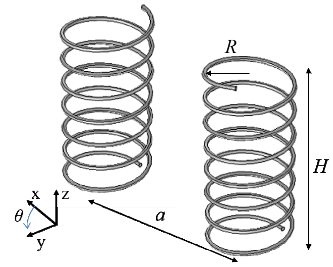

Fig.2. Schematic representation of the helices. $H = 8.75$ mm – height, $R = 2$ mm – radius, a – distance between helices centers.

Far field measurements were undertaken at 1 m distance from the dimers using a half wavelength dipole antenna with 1.5 GHz resonant frequency. Experimental data for the electric fields were obtained using a 40 GHz Vector Network Analyzer Anritsu MS4644A and possible reflections and noise were suppressed by using an electromagnetic anechoic chamber formed of ECCOSORB AN-77.

III. DISCUSSION

Experimental, analytical and numerical data were obtained for the described configuration of helices. In Fig. 3 one can see experimental results for the frequency dependence of the directivity for different distances between helices. It can be seen that the optimum spacing is $a = 16$ mm, which is almost 3 times smaller in size as compared to the superdirective dimers previously demonstrated [16]. A maximum directivity of 5.05, which is close to the theoretical maximum, is measured at 1.521 GHz. In this case the operational bandwidth (calculated at the level of −3 dB) is 14 MHz which is 1 % of the resonant frequency. Fig. 4 illustrates a comparison between the analytical, numerical and experimental directivity data close to the frequency of directivity maximum. High uncertainties at low and high frequencies are associated with the very small magnitude of signals away from resonance.

By increasing the distance between the elements we also decrease the coupling between them, which results in a narrowing of the operational band. In contrast, for smaller distances and stronger coupling the operational band widens and reaches 20 MHz for 12 mm separation. However the maximum of the directivity for this case, $D_{\max} = 4.32$ at 5.1 GHz, is significantly smaller than that for the optimal configuration.

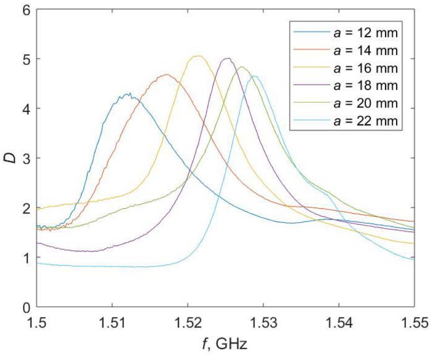

Fig. 3. Experimental results for the frequency dependence of the directivity for $a = 12 – 22$ mm between helices

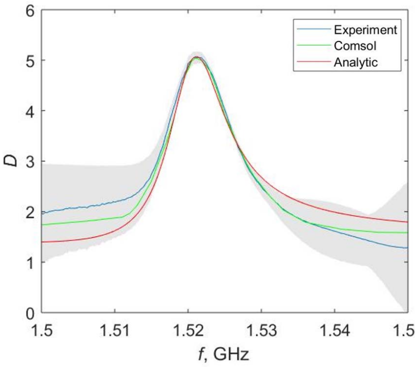

Fig. 4. Analytical numerical and experimental frequency dependencies of directivity for superdirective dimer with $a = 16$ mm. Uncertainties for experimental value are marked in grey.

The directivity patterns for the optimum configuration at *f* = 1.515, 1.521 and 1.527 GHz are presented in Fig. 7. At low frequencies power is radiated equally in both forward and backward direction. At the maximum directivity frequency, as predicted analytically, most power is radiated in the backward direction, while for all other directions radiation is suppressed through destructive interference. For higher frequencies the angular width of the backward lobe grows leading to a decrease in directivity. Good agreement between analytical, numerical and experimental data is also observed here for all frequencies.

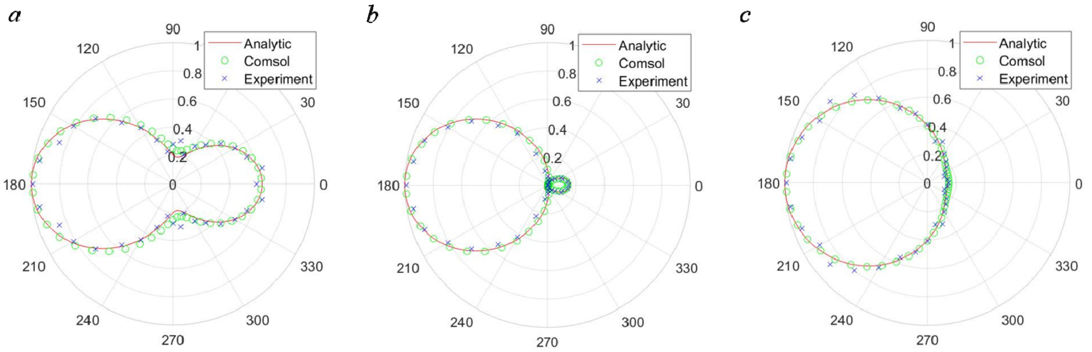

Fig.5. Analytical numerical and experimental directivity patterns for a superdirective dimer with a = 16 mm. *a)* *f* = 1.515 GHz, *b)* *f* = 1.521 GHz, c) *f* = 1.527 GHz

CONCLUSIONS

Superdirective dimers with directivity values of $D > 5$ have been experimentally demonstrated in the low GHz frequency range. The helical geometry used provides more than a 3-times size reduction by comparison to previous split-ring versions and has permitted the use of strong inductive feeding with 78% efficiency. Numerical and analytical results are shown to be in good agreement with experimental data. The radiation properties of this structure have been studied as a function of the distance between the elements. The presented results prove the possibility of reaching close to the theoretical maximum directivity values and provides a basis to construct superdirective arrays with larger numbers of elements.

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