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Novel Electrically Small Spherical Electric Dipole Antenna

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ABSTRACT: This paper introduces a novel electrically small spherical meander antenna. Horizontal sections of the meander are composed of wire loops, radii of which are chosen so that the whole structure is conformal to a sphere of radius a . To form the meander the loops are connected by wires at a meridian plane. The antenna operates as an electric dipole, i.e. it radiates the TM_{10} spherical mode. The antenna is self-resonant and can be matched to a wide range of input feed lines without an external matching network. In this paper, a spherical meander antenna of the size $ka = 0.27$ and the input impedance of 72 ohms is numerically investigated and its performance is compared to that of the multiarm spherical helix antenna of the same size. Both antennas yield equal quality factors, which are about 1.5 times the Chu lower bound, but quite different cross-polarization characteristics.

INTRODUCTION

In the last two decades we have witnessed a tremendous growth of wireless communication systems and services. This process attended with continuing miniaturization of portable communication devices necessitates the development of physically small antennas, which in many cases means electrically small. Since early works by Wheeler [1] and Chu [2], it has been known that the electrical performance of electrically small antennas (ESA) is subject to certain limitations. The minimum radiation quality factor of an electrically small dipole antenna inscribed in a sphere of radius a can be expressed as [3]

$$Q_{LB} = \frac{1}{(ka)^3} + \frac{1}{ka}, \quad (1)$$

where k is the free space propagation constant. This ultimate lower bound, sometimes referenced as the Chu lower bound, is obtained under an assumption that there is no stored electric energy for an electric dipole antenna (magnetic energy for a magnetic dipole antenna) inside the minimum sphere of radius a . Less conservative bounds derived by Thal [4] for source currents located on the surface of the minimum sphere account for the corresponding stored energies inside that sphere. For electric and magnetic ESA these bound are $Q \rightarrow 1.5Q_{LB}$ and $Q = 3.0Q_{LB}$, as $ka \rightarrow 0$, respectively. Multiarm spherical helix wire [5] and slot [6] antennas are examples of electrically small electric and magnetic dipole antennas, respectively, that approach the Thal bounds. Recently, three novel electrically small magnetic dipole antennas with $Q \rightarrow 3.0Q_{LB}$ were presented in [7].

In this paper, a novel electrically small electric dipole antenna is introduced. The antenna is a self-resonant spherical meander radiating the TM_{10} spherical mode. The radiation quality factor of this antenna approaches the bound $1.5Q_{LB}$. A comparison is made to another electrically small electric dipole antenna – the multiarm spherical helix [8]. Numerical results presented here are obtained with the surface integral equation technique [9] assuming perfectly electrically conducting wires and a delta gap voltage generator.

SPHERICAL MEANDER ANTENNA

As sketched in Fig 1, wire loops are equidistantly arranged in θ over the antenna spherical surface. With wires connecting the loops in the XZ-plane, the whole structure becomes a meander, which is particularly evident from the side view of the antenna in Fig. 2. Obviously, for an electrically small antenna horizontal meander sections formed by the wire loops contribute weakly to the antenna far fields due to the symmetry and oppositely directed currents. However, although the main radiation is due to the vertical wires, the loops play an important role in reducing the antenna resonance frequency. Consider the spherical meander antenna with radius

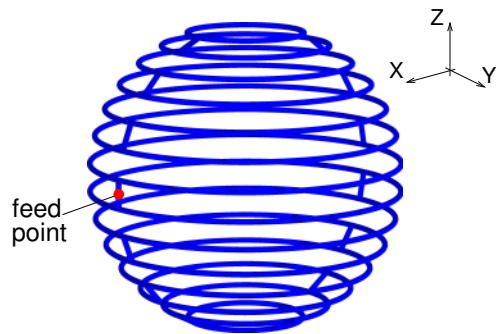


Fig. 1. Spherical meander antenna.

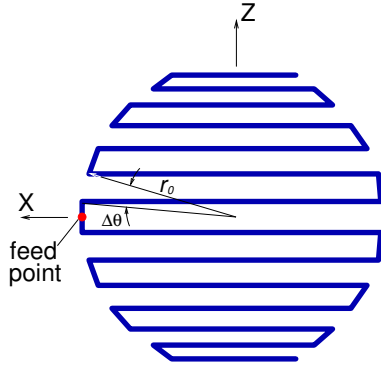


Fig. 2. Side view of the spherical meander antenna.

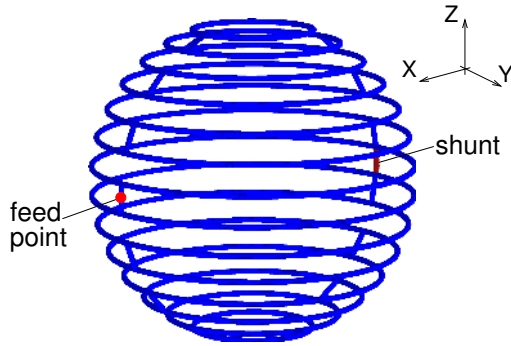


Fig. 3. The shunt-matched spherical meander antenna.

Tab. 1. Characteristics of the spherical meander antenna.

Number of loops	$\Delta\theta$	f_0 , MHz	R_0 , Ω	Q/Q_{LB}
0	–	1058	48.5	3.11
6	30.0	357.5	2.8	2.04
10	17.6	300.2	1.9	1.81
16	10.5	269.5	1.5	1.71
14 (flat)	10.5	373.5	2.9	3.66
16 + shunt	10.5	300.4	71.8	1.68

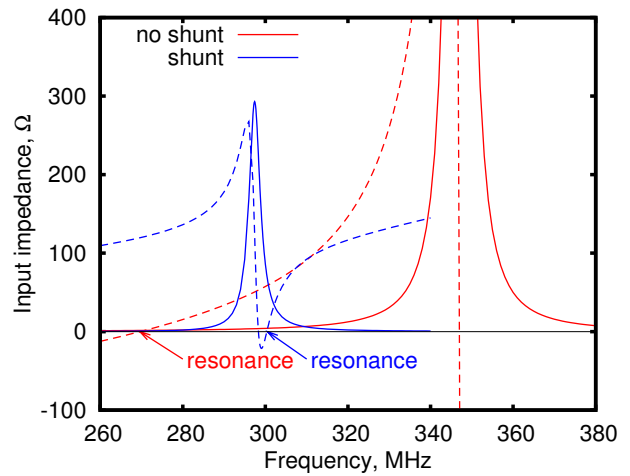


Fig. 4. Input impedance of the spherical meander antenna with and without shunt.

$r_0 = 42.2$ mm made of wire $2r_w = 2.6$ mm in diameter. The antenna radius r_0 is measured from the origin to the wire axes, and thus, the antenna occupies a spherical volume of radius $a = r_0 + r_w = 43.5$ mm. Tab. 1 summarizes the resonance frequency f_0 , the resonance input resistance R_0 , and the ratio Q/Q_{LB} of the antenna for various values of $\Delta\theta$. It is observed that the resonance frequency reduces almost by factor of four as the number of loops increases from 0 (simple curved dipole) to 16, although the total length of the vertical wire sections remains approximately the same. Moreover, the ratio Q/Q_{LB} drops from 3.11 to 1.71. The spherical meander antenna also shows favorable performance characteristics as compared to a flat meander antenna, whose cross section coincides with the side view in Fig. 2. Thus, parasitic capacitors formed by the horizontal loops not only make the spherical meander antenna electrically small, but also reduce the relative part of the reactive energy stored inside the spherical antenna volume.

The only problem, however, is that the input resistance at the resonance drops to unacceptably small values. By applying a shunt wire as shown in Fig. 3, the input resistance is raised to 72 ohms (Tab. 1). The input impedance behavior versus frequency changes from the dipole-like to loop-like, that is the antiresonance occurs first (Fig. 4). The shunt can be applied not only at the position opposite to the feed point, but at any position between the two central loops, and in this way can match the antenna to a wide range of input feed lines.

COMPARATIVE ANALYSIS OF MEANDER AND HELIX ELECTRICAL DIPOLE ANTENNAS

In this section, the shunt-matched spherical meander antenna described above is compared to a multiarm spherical helix antenna. As sketched in Fig. 5, the geometry for the later consists of top and bottom symmetric hemispheres composed of four helical arms with 1.5 turns in each [6, Section III]. Both antennas have the same radius $r_0 = 42.2$ mm and wire diameter $2r_w = 2.6$ mm; both are assumed to be lossless. Both antennas radiate the TM_{10} spherical mode and yield Q 's that are close to the bound $1.5Q_{LB}$ predicted by Thal [4].

Fig. 6 plots the input impedance of the antennas versus frequency. The geometry of the meander antenna is adjusted to realize the resonance at nearly the same frequency as the helix antenna. The meander antenna delivers 71.8 ohms input resistance at the resonance, whereas the helix antenna yields 48.8 ohms. Despite the appreciable differences in the input impedance behavior, both antennas exhibit nearly the same reflection coefficient, when it is normalized to 75 and 50 ohms, respectively (Fig. 7). Consequently, the Q factors are nearly the same as well (Tab. 2).

At this point, it is important to note that the choice of the radius of the minimum sphere a significantly affects the ratio Q/Q_{LB} . There are two approaches pursued in the literature with respect to spherical wire antennas. The first one, which appears to be followed in [8, 6], assumes the minimum sphere radius coincides with the antenna radius $a = r_0$, i.e. axes of the wires lie along the surface of the minimum sphere. Thus, half of a wire remains outside the minimum sphere. In the the second approach, the whole wire is enclosed in the minimum sphere, that is $a = r_0 + r_w$ [7, 10]. The results of these two approaches are summarized in Tab. 2. It is observed that the first approach results in $Q/Q_{LB} = 1.54$ and $Q/Q_{LB} = 1.53$ for the meander and helix antennas, respectively. The later value of Q/Q_{LB} agrees with the result reported in [6]. The second approach yields $Q/Q_{LB} = 1.68$ and $Q/Q_{LB} = 1.67$, respectively, which is still close to the Thal bound $Q/Q_{LB} = 1.5$ for an electrically small electric dipole antenna, but appreciably higher as compared to the first approach.

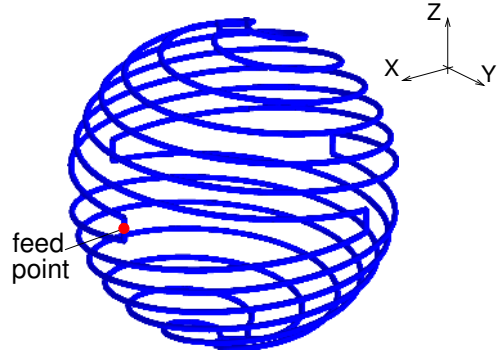


Fig. 5. 4-arm spherical helix antenna [8, 6].

Tab. 2. Characteristics of the meander and helix antenna.

	$a = r_0 = 42.2 \text{ mm}$						$a = r_0 + r_w = 43.5 \text{ mm}$		
	$f_0, \text{ MHz}$	R_0, Ω	Q	ka	Q_{LB}	Q/Q_{LB}	ka	Q_{LB}	Q/Q_{LB}
meander	300.4	71.8	88.0	0.266	57.1	1.54	0.274	52.3	1.68
helix	300.6	48.8	87.2	0.266	57.0	1.53	0.274	52.2	1.67

Since the meander and helix antennas are electrically small, the TM_{10} spherical mode dominates in their radiation spectrum, and their radiation patterns closely reproduce that of an elementary electric dipole (Fig. 8). However, their cross-polarization characteristics are quite different. (Here, the the cross-polarization is understood according to the Ludwig's second definition [11].) For the meander antenna, the TE_{11} spherical mode is responsible for the cross-polarization, whereas for the helix antenna, it is the TE_{20} mode. Consequently, the cross-polarization pattern of the helix antenna is omnidirectional (Fig. 8b), whereas the meander antenna radiates the cross-polar component only in the YZ -plane (Fig. 8a).

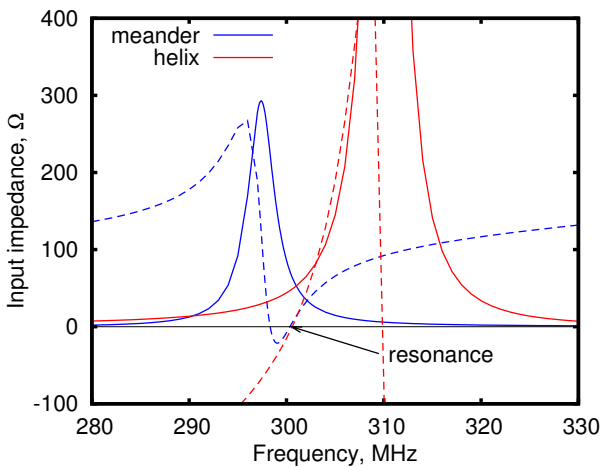


Fig. 6. Input impedance of the meander and helix antennas.

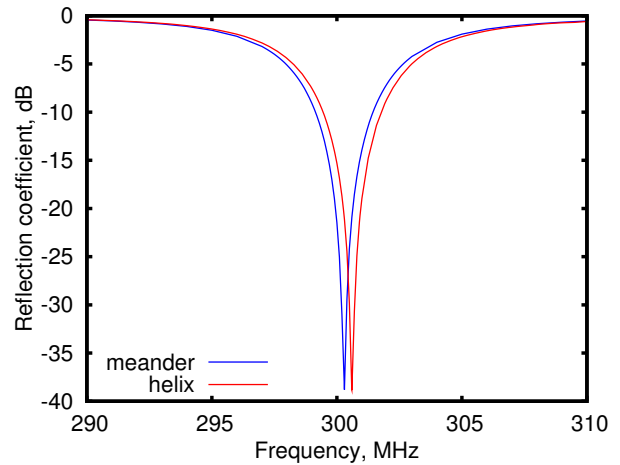


Fig. 7. Reflection coefficient of the meander and helix antennas with respect to 75 and 50 ohms, respectively.

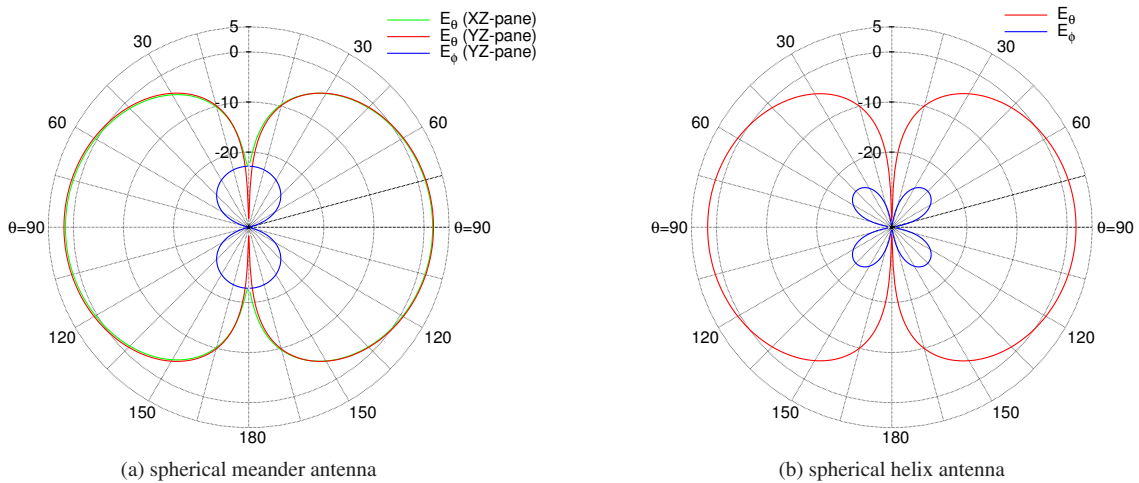


Fig. 8. Radiation patterns of the electrically small electric dipole antennas (vertical plane, in dBi).

CONCLUSION

Spherical meander antenna is presented and numerically investigated. Due to closely spaced horizontal loop-shaped meander sections the antenna is able to operate in the electrically small regime. It is self-resonant and radiates the TM_{10} spherical mode, and thus, akin to the multiarm spherical helix antenna [8]. Results of the numerical investigations reveal very similar performance of both antennas, which differ mainly in the distribution of the horizontally polarized (cross polar) component. It is also shown how important it is to define clearly the radius of the minimum sphere, since this has significant effect on the Q/Q_{LB} ratio of an electrically small antenna.

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