OPTIMIZATION OF HELICAL ANTENNAS

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ABSTRACT

Helical antennas have been known for a long time, but the literature is overwhelmed with controversial information about their performance. We have systematically investigated helical antennas located above an infinite ground plane and obtained design curves. We have also observed that the shape and size of the ground conductor have influence on the helical antenna performance. By optimizing the dimensions of ground conductors that have the form of a cup and a cone, we have significantly increased the antenna gain. Simultaneous optimization of the helix and the ground conductor is under way to improve the antenna performance.

1. INTRODUCTION

Helical antennas that radiate in the axial mode have been used in mobile and satellite communications for a long time. However, some frequently used design data [1]-[4] are in discrepancy with experimental results [5], [6] and other theoretical results [7], [8]. These differences have motivated us to make systematic investigation of characteristics of uniformly-wound helical antennas located above an infinite ground plane. We assembled design curves for such antennas [9], which are summarized in Section 2.

The gain of the helical antenna is significantly affected by the shape and size of the reflector (counterbalance). Usually, the reflector has the shape of a flat square or circle, or it has the form of a circular cup. However, this fact is not widely exploited in the literature. In [10], we compared various reflectors and demonstrated a significant increase in the antenna gain by properly shaping the reflector. In [11], we presented the first results of the optimization for the helical antenna and the reflector. Finally, in [12], we provided physical explanations for the increased gain provided by the optimally-shaped reflector. All these results are summarized in Section 3.

In order to provide useful design data, further optimization is required, which should involve additional parameters and cover wider ranges of parameters compared to [11]. The optimization tasks are summarized in Section 4.

2. HELICAL ANTENNA ABOVE INFINITE GROUND PLANE

Figure 1 shows a uniformly-wound helical antenna above infinite ground plane. The geometry of the helical antenna is defined by the number of turns (N), helix pitch (p), helix radius (a), and wire radius (r). The helix length is $L = Np$, the helix circumference is $C = 2\pi a$, and the pitch angle is $\alpha = \arctan(p/C)$.

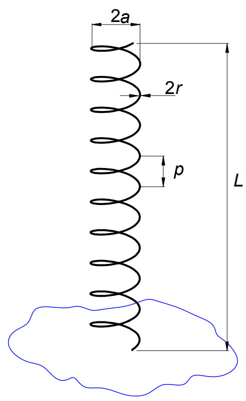

Figure 1. Helical antenna above infinite ground plane.

According to the classical design data [2], the helical antenna operates in the axial mode in the frequency band where $3/4 < C/\lambda < 4/3$ ($0.8 < C/\lambda < 1.2$ in [3]). The wire diameter has practically no influence on the antenna characteristics [4] in a wide range $0.005 < d/\lambda < 0.05$. Based mostly on experimental research, the optimal pitch angle was established to be in a relatively narrow range $12° < \alpha < 14°$ ($12° < \alpha < 15°$ in [2]). Within the operating frequency band, the antenna gain varies with frequency. The maximal antenna gain occurs near the upper edge of the operating frequency band, when $C/\lambda_p \approx 1.1-1.2$ [4] (λ_p is the wavelength at the frequency where the maximum occurs). The minimum number of turns is about $N = 4$. The size and shape of the ground plane are not critical [2], [3]. Typically, square or circular flat plates are recommended. The minimal size of the square plate (or the minimal circle diameter) is $b/\lambda_c = 0.75$ [2] ($b/\lambda_c = 0.5$ in [3]), where λ_c is the wavelength at the central frequency. An empirical relation between the antenna gain and the helix length is [1]

$$g_{[\mathrm{dBi}]} = 10\log\left(15\left(\frac{C}{\lambda}\right)^2 \frac{L}{\lambda}\right). \quad (1)$$

Equation (1) holds for constant-pitch helices with $12° < \alpha < 15°$, $3/4 < C/\lambda < 4/3$, and $N > 3$.

In [10], we considered optimal antennas for narrowband applications (NB design) and for broadband applications (WB design). We considered the total gain variations within the band of 1 dB, 2 dB, and 3 dB. These three cases are denoted as WB1, WB2, and WB3 design, respectively. We analyzed large number of helical antennas using programs from References [13] and [14] and compiled the results.

Figure 2 compares various results for the maximal gain of the helical antenna as a function of the normalized axial length. The results given by the classical equation (1) overestimate the gain. Our NB design agrees well with the design curve from [8] and our WB3 design is slightly better than the simulation data from [7]. The experimental data [5], [6] were obtained using a reflector in the form of a cup. This reflector enhances the gain for longer helices, which explains the steep slope of the experimentally obtained curve.

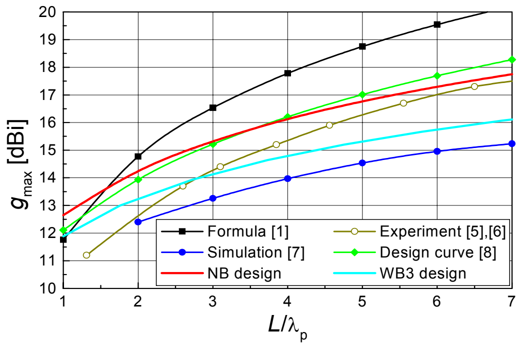

Figure 2. Antenna gain versus normalized antenna length. Comparison of results obtained by: theoretical formula [1], experiment [5], [6], simulation [7], design curve [8], and our computations for narrowband design (NB) and 3 dB wideband design (WB3).

A summary of the key design data obtained from our computation is given in Figures 3-5. Figure 3 shows the maximal gain, Figure 4 shows the optimal circumference, and Figure 5 shows the optimal pitch angle (with the wire radius as the parameter).

The optimal pitch angle strongly depends on the wire radius and the desired gain variations within the operating band (which does not fit into the well-established belief). The optimal pitch angles are in the range $3° < \alpha < 16°$. This is significantly wider than the classical range ($12° < \alpha < 14°$).

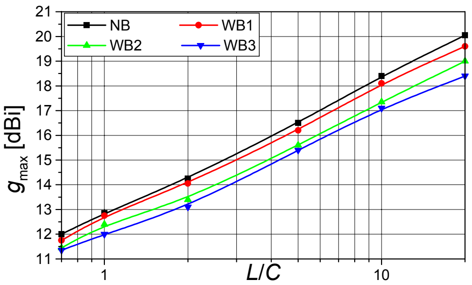

Figure 3. Maximal antenna gain versus normalized antenna length.

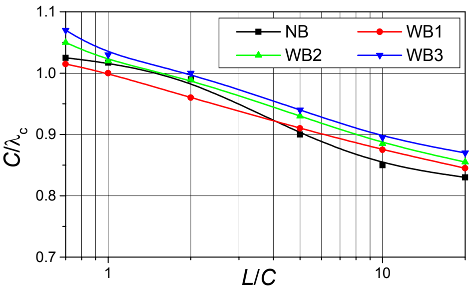

Figure 4. Normalized circumference at central frequency versus normalized antenna length.

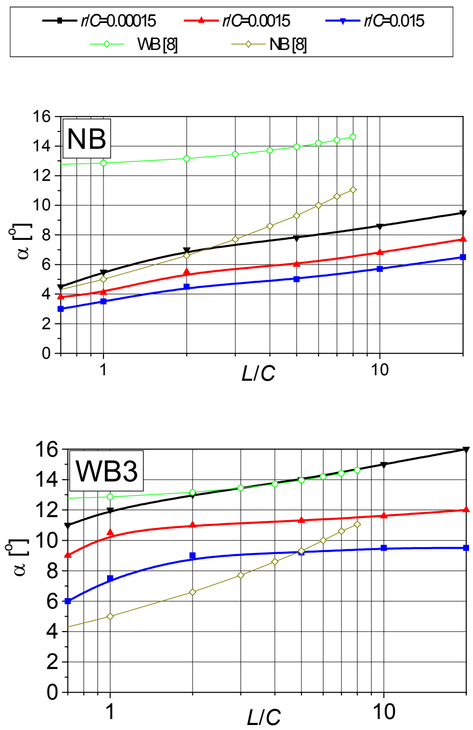

Figure 5. Optimal pitch angle versus normalized antenna length with normalized wire radius as parameter for the NB and WB3 design.

3. INFLUENCE OF THE REFLECTOR

We have found that the size and shape of the ground conductor (reflector) of helical antennas have significant impact on the antenna gain. By shaping the ground conductor, we increased the gain of a helical antenna for several dB compared to the case when the helical antenna is above an infinite ground plane.

We analyzed a helical antenna above an infinite ground plane, a finite-size square reflector, a cup, and a cone (Figure 6).

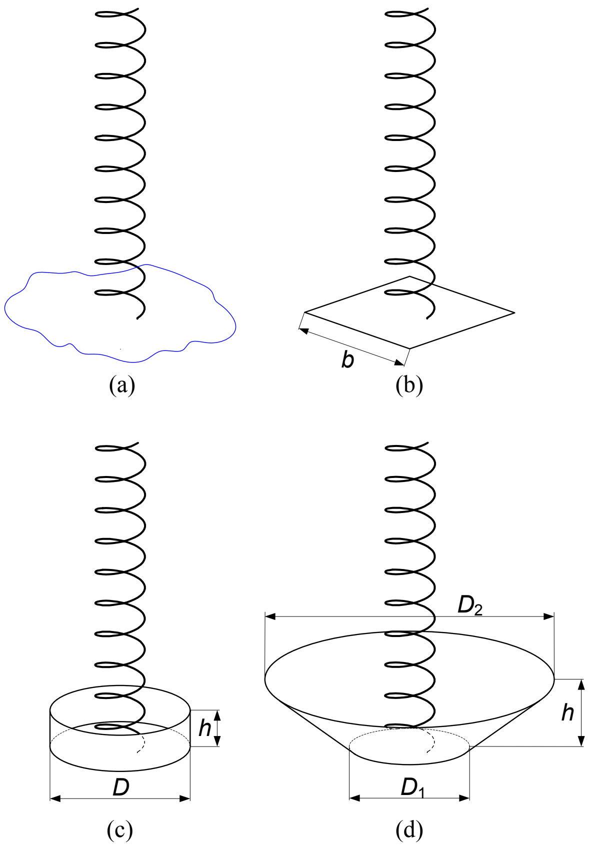

Figure 6. Helical antenna above (a) infinite ground plane, (b) square conductor, (c) cylindrical cup, and (d) truncated cone.

In [10], we found that the optimal size of the square conductor (which gives high gain and broadband performance) is $b = 1.5\,\lambda$. The optimal dimensions of the cylindrical cup are $D = 1\,\lambda$ and $h = 0.25\,\lambda$. The optimal dimensions of the truncated cone are $D_1 = 0.75\,\lambda$, $D_2 = 2.5\,\lambda$, and $h = 0.5\,\lambda$. The typical gain as the function of frequency, for various reflectors, is shown in Figure 7.

In [11], optimization of dimensions of the truncated cone was performed, together with the optimization of the helix pitch and circumference. Antenna optimizations are carried out using particle swarm optimization (PSO) [15] and Nelder-Mead simplex algorithm [16] utilized in WIPL-D optimizer. For larger reflectors, the optimal pitch angles have unexpectedly large values of about 30°. The results for the antenna gain are summarized in Figure 8. Several sets of results are shown. The first set is taken from [17]. It consists of compiled data for helical antennas as well as the gain estimation based on the Hansen-Woodyard condition. Figure 8 also presents data for optimal helical antennas above infinite ground plane taken from [9] for the narrowband (NB) and wideband (WB3) designs. Finally, data are given for optimal helical antennas with truncated cones [11] for two cone heights. Note that for tall cones, the length (L) of the helix has practically no influence on the gain. This fact indicates that the cone is the main source of radiation, acting like a horn antenna [18].

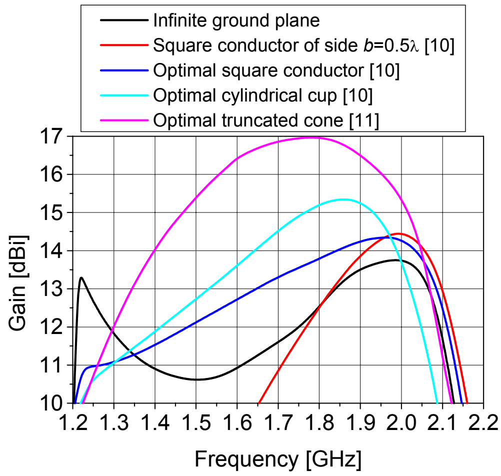

Figure 7. Gain for various shapes of the ground conductor.

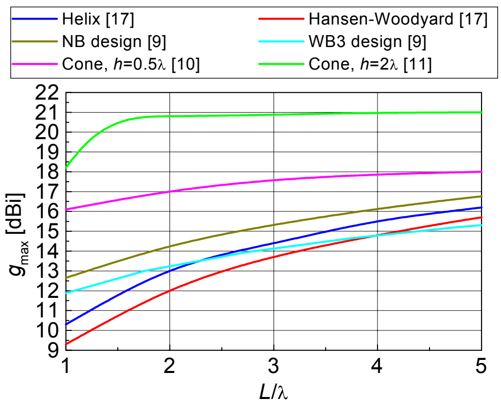

Figure 8. Gain comparison.

In [12], we investigated the physical causes of increased gain when using a properly dimensioned reflector. We evaluated the current distribution in the helix and the ground conductor, and calculated contributions of various parts of the system. We established that an infinite ground plane has favorable effect at lower frequencies. It can make the performance of some helical antennas more broadband by reflecting waves launched from the helix downwards. However, broadband helical antennas have lower peak gain than narrowband antennas.

The major source of spillover is the current in the lowest few turns of the helix. This current creates strong sidelobes at low elevation angles. Increasing the intensity of the traveling wave on the helical antenna yields radiation patterns with lower sidelobes.

A cylindrical ground conductor with a rim (a cup) and a conical reflector prevent propagation of the spillover fields in horizontal directions and direct them upwards. A large cone has additional favorable effect, as it acts like a horn antenna and further increases the gain in the zenith direction.

The radiation pattern is significantly improved if the radiation from the lowest few turns is suppressed. This can be achieved by using various launchers [19] or simply by reducing the helix pitch. For such antennas, the influence of the ground conductor on the radiation pattern is small.

4. PROPOSED ACTIVITIES

In order to provide a full set of design data for helical antennas with optimal reflectors, further optimization is needed. Previous optimizations involved only one wire radius. However, results for a wide range of wire radii are required.

Previous optimizations were restricted to cone heights up to two wavelengths. Larger heights are to be included to cover the transition of a helix with a conical reflector to a helicone antenna.

Finally, the optimization should include variable pitch and helix circumference to compare the influence of the reflector to the influence of wave launchers.

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REFERENCES

[1] J.D. Kraus, "Helical beam antennas," *Electronics*, **20**, 109-111, April 1947.
[2] J.D. Kraus, *Antennas*, New York: McGraw-Hill, 1988.
[3] G.A. Thiele, W.L. Stutzman, *Antenna Theory and Design*, New York: J. Wiley, 1981.
[4] T.E. Tice and J.D. Kraus, "The influence of conductor size on the properties of helical beam antennas," *Proceedings IRE*, **27**, 1296, November 1949.
[5] H.E. King and J.L. Wong, "Characteristics of 1 to 8 wavelength uniform helical antennas", *IEEE Transactions on Antennas and Propagation*, **AP-28**, 291-296, March 1980.
[6] J.L. Wong and H.E. King "Empirical helix antenna design" *Antenna and Propagation Society International Symposium*, vol. 20, 366-369, May 1982.
[7] D.T. Emerson, "The gain of the axial-mode helix antenna," *Antenna Compendium*, **4**, 64-68, 1995.
[8] *Poynting*, "Helical antenna design curves", www.poynting.co.za/tech_training/helical.shtml.
[9] A.R. Djordjević, A.G. Zajić, M.M. Ilić, and G.L. Stueber, "Optimization of helical antennas ", *IEEE Antennas and Propagation Magazine*, vol. 48, no. 6, December 2006, pp. 107-115.
[10] A.R. Djordjević, A.G. Zajić, and M.M. Ilić, "Enhancing the gain of helical antenna by shaping the ground conductor", *IEEE Antennas and Wireless Propagation Letters*, Vol. 5, 2006, pp. 138-140.
[11] D.I. Olcan, A.G. Zajić, M.M. Ilić, and A.R. Djordjević, "On the optimal dimensions of helical antenna with truncated-cone reflector", *Proceedings of EuCAP 2006*, ESA SP-626, Nice, November 2006.
[12] A.R. Djordjević, M.M. Ilić, A.G. Zajić, D.I. Olcan, and M.M. Nikolić, "Why does reflector enhance the gain of helical antennas?", accepted for presentation at *EuCAP 2007*, Edinburgh, November 2007.
[13] A.R. Djordjević, M.B. Baždar, T.K. Sarkar, and R.F. Harrington, *AWAS for Windows: Analysis of Wire Antennas and Scatterers, Software and User's Manual*, Boston: Artech House, 2002.
[14] B.M. Kolundžija et al., *WIPL-D Professional v5.1*, WIPL-D, 2005, http://www.wipl-d.com
[15] J. Robinson and Y. Rahmat-Samii, "Particle swarm optimization in Electromagnetics" *IEEE Trans. on Antennas and Propagation*, Vol. 52, 2004, pp. 397-407.
[16] J.A. Nelder, R. Mead "A simplex method for function minimization", *The Computer Journal* 7, 1965, pp. 308-313.
[17] T.A. Milligan, *Modern Antenna Design*, Hoboken, N.J.: J. Wiley, 2005, Figure 10-2.
[18] K.R. Carver, "The helicone – a circularly polarized antenna with low sidelobe level", *Proc. IEEE*, Vol. 55, 1967, p. 559.
[19] D.J. Angelakos and D. Kajfez, "Modifications on the axial-mode helical antenna", *Proceedings of IEEE*, **55**, pp. 558-559 (1967).