ON THE OPTIMAL DIMENSIONS OF HELICAL ANTENNA WITH TRUNCATED-CONE REFLECTOR

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ABSTRACT

This paper presents optimization of a helical antenna with a truncated-cone reflector. We have found that the dimensions of the truncated-cone reflector and the dimensions of the helical antenna need to be optimized simultaneously to obtain the optimal design. Furthermore, we have found that the truncated-cone reflector can significantly increase the gain of the helical antenna compared to a circular or a square flat reflector. A set of diagrams is made to enable simple design of helical antennas with truncated-cone reflectors. Finally, the results are experimentally verified.

1. INTRODUCTION

Axial-mode helical antennas have been used in mobile and satellite communications for a long time [1]. The helical antenna is often located above a conducting ground plane. Usually, the ground plane has the shape of a flat plate (e.g., square or circular) [1]. In [2], a circular cup is used as a ground plane. In [3], a hybrid between a helical antenna and a circular horn is proposed, which has a high gain. In [4], all these shapes of the ground (counterbalance) are analyzed. The obtained results show that the gain of the helical antenna is significantly affected by the shape and size of the ground conductor. In [4], a truncated-cone reflector was proposed. Although it was shown in [4] that the truncated-cone reflector has the highest impact on increasing the antenna gain, the optimal dimensions of the reflector are still an open question.

The aim of this paper is to optimize the dimensions of the truncated-cone reflector and the dimensions of the helical antenna to maximize the gain in the axial direction. We have found that the dimensions of the truncated-cone reflector and the dimensions of the helical antenna need to be varied simultaneously to obtain the optimal design. Based on extensive computations, diagrams are made that enable simple design of helical antennas with truncated-cone reflector.

The paper is organized as follows. Section 2 describes geometry of the helical antenna with truncated-cone reflector. Section 3 describes simulations and presents diagrams from which the optimal parameters of the helical antenna with truncated-cone reflector can be extracted. Section 4 presents the experimental verification of the design procedure. Finally, Section 5 concludes the paper.

2. GEOMETRY OF HELICAL ANTENNA WITH TRUNCATED-CONE REFLECTOR

The helical antenna with the truncated-cone reflector is shown in Fig. 1. The antenna is assumed to be in a vacuum and to operate only in the axial mode.

The helical antenna consists of a conductor bent in the form of a helix. Parameters of the helix are the overall length (L), the radius of the imagined cylinder on which the helix is wound (R), the pitch angle of the helix (α), and the wire radius (a). The pitch angle of the helix is given by $\alpha = \mathrm{arctg}\big((L/N)/2\pi R\big)$, where N is the total number of turns of the helix. Only uniform helices are considered in this paper (i.e., the cylinder diameter and the pitch angle are constant along the helix axis).

The antenna reflector (counterbalance) has the form of a truncated-cone. Parameters of the truncated-cone reflector are the height (H), the lower radius (R_{lower}), and the upper radius (R_{upper}).

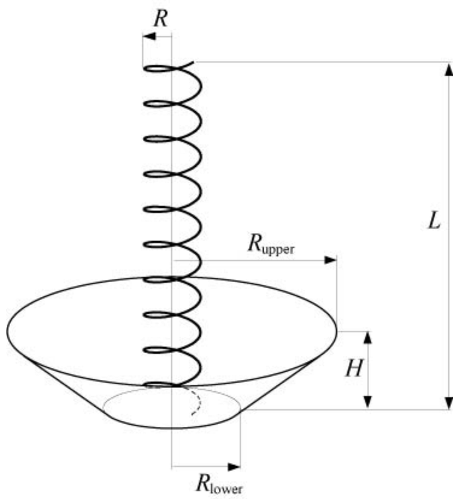


Figure 1. Helical antenna with truncated-cone reflector

3. SIMULTANEOUS OPTIMIZATION OF HELIX AND TRUNCATED-CONE PARAMETERS

In this section, we simultaneously optimize the parameters of the helix and the truncated-cone reflector to maximize the antenna gain. The optimization of the antenna parameters for the maximal gain depends on the type of application (narrowband or broadband). In this paper, we consider only narrowband applications. Our objective is to maximize the gain at a single frequency, for a fixed helix length (L) and a fixed reflector height (H). Additionally, we control the axial ratio (which defines the quality of the circular polarization) by keeping it as close as possible to 1.

The antenna is modeled and analyzed using the electromagnetic (EM) solver WIPL-D [5]. The circular truncated cone is approximated by a truncated pyramid with six identical flat surfaces. All antenna dimensions are normalized with respect to the wavelength (λ) at the operating frequency. In all cases, we take the normalized wire radius to be $a/\lambda = 0.0015$.

We take three families of helical antennas. Each family has a constant length of 1, 2, and 5 wavelengths, respectively (i.e., $L/\lambda = 1, 2, \text{and } 5$). For each family, eight normalized heights of the cone reflector are considered: $H/\lambda = 0.25$, 0.5, 0.75, 1, 1.25, 1.5, 1.75, and 2.

For each pair of L/λ and H/λ, four parameters are varied (optimized): the helix radius (R), the pitch angle (α), the lower radius of the truncated cone (R_{lower}), and the upper radius (R_{upper}). No losses are taken into the account in the simulation model because our experience shows that the losses have minor effect on the antenna performance.

Antenna optimizations are carried out using Particle Swarm Optimizer (PSO) [6] utilized in the WIPL-D Optimizer. The setup of the Particle Swarm Optimizer is as follows: the total number of particles 15, the inertia coefficient $w = 0.73$, and the social-rate and cognitive coefficients $(c_1, c_2) = (1.496, 1.496)$. PSO is used since it has been found to be very efficient for antenna optimization when the number of optimization variables is about 5. One optimization cycle consists of 300 iterations (EM solver calls).

Each optimization is carried out 10 times with a random-seeded initial set of solutions (swarm) to maximize the possibility of finding the best solution in the optimization space. Upon the end of all repetitions of the PSO optimization, the best-found solution in all restarts is the solution taken as the final result.

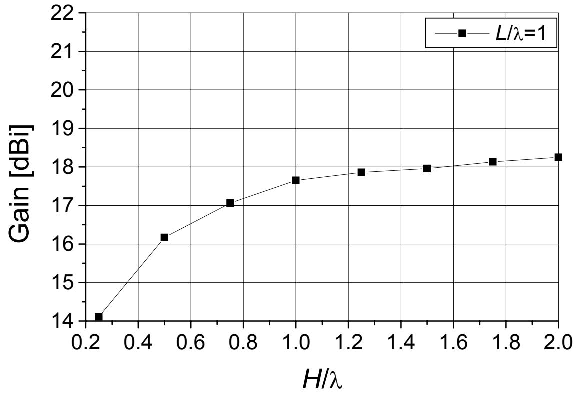
The obtained solutions are crosschecked using a combination of the random search and the Nelder-Mead simplex algorithm (RSNM) [7]. Both algorithms are implemented in the WIPL-D Optimizer. A random point is used as the starting point for the Nelder-Mead simplex algorithm, which is considered to be one of the most robust algorithms for the local optimization. To provide fair comparison, we take the same total number of EM solver calls for RSNM and PSO. It is found that RSNM converges to the solution with approximately two times fewer EM solver calls than PSO. Hence, RSNM is repeated 20 times, again with the aim to maximize the possibility of finding the global solution (rather than finding local solutions, which are usually suboptimal). For all results presented in this paper, PSO and RSNM yield the same optima. The results of the numerous simulations are collected and presented in the following figures.

Fig. 2 presents the optimal antenna gain as a function of the normalized truncated-cone height for normalized helix lengths $L/\lambda = 1$, $L/\lambda = 2$, and $L/\lambda = 5$. By comparing the results shown in Fig. 2 with the results for an optimal flat (square) reflector [1], we note an increase in gain of about 1 dB for $H/\lambda = 0.25$ and up to about 5 dB for $H/\lambda = 2$.

Fig. 3 shows the optimal pitch angle versus the normalized truncated-cone height for normalized helix lengths $L/\lambda = 1$, $L/\lambda = 2$, and $L/\lambda = 5$. The optimal pitch angle at first increases with increasing the cone height. For taller cones, the angle remains almost constant (about 25-30°). In this region, the antenna gain has very small variations when the pitch angle is varied even for several degrees. Hence, the optimal data look as if they are very noisy. For $L/\lambda = 1$ and very tall cones ($H/\lambda > 1.25$), the optimal pitch angle decreases. In these cases, the conical reflector is taller than helix. Hence, we have the case of a circular horn antenna excited with a helix placed inside the horn [3].

Fig. 4 shows the optimal normalized helix radius versus the normalized truncated-cone height for normalized helix lengths $L/\lambda = 1$, $L/\lambda = 2$, and $L/\lambda = 5$.

Finally, Fig. 5 presents the optimal normalized cone radii versus the normalized truncated-cone height for normalized helix lengths $L/\lambda = 1$, $L/\lambda = 2$, and $L/\lambda = 5$. For all helices considered here, the optimal lower cone radius is almost constant, $R_{\text{lower}}/\lambda \approx 0.5$. The upper radius increases with increasing the cone height, approximately following the straight line $R_{\text{upper}}/\lambda = 0.5H/\lambda + 1$.



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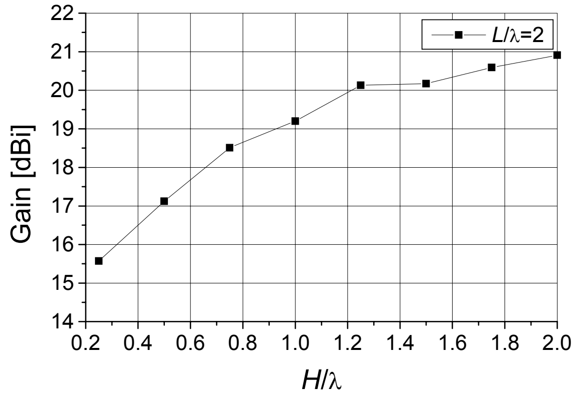

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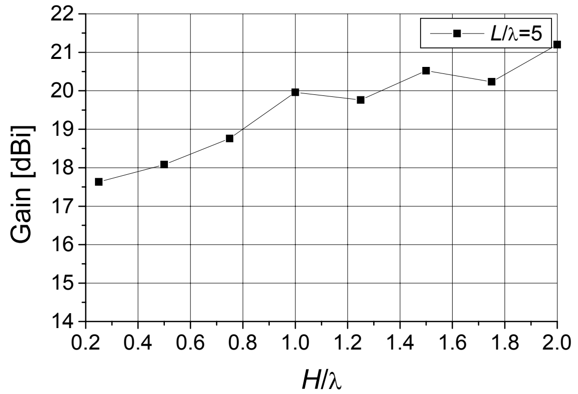
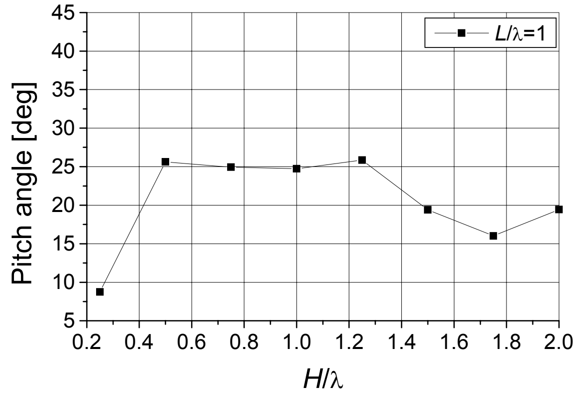


(c)

Figure 2. Maximal antenna gain versus normalized truncated-cone height for normalized helix lengths (a) $L/\lambda = 1$, (b) $L/\lambda = 2$, and (c) $L/\lambda = 5$



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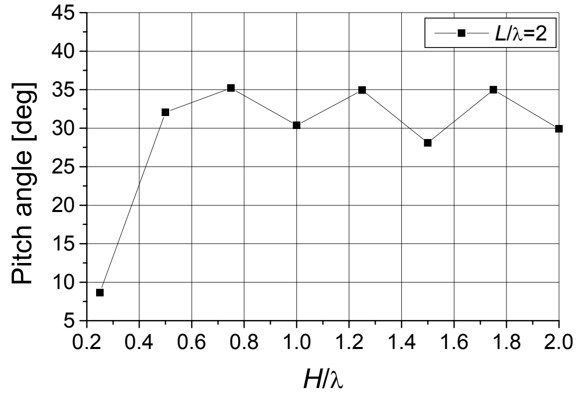

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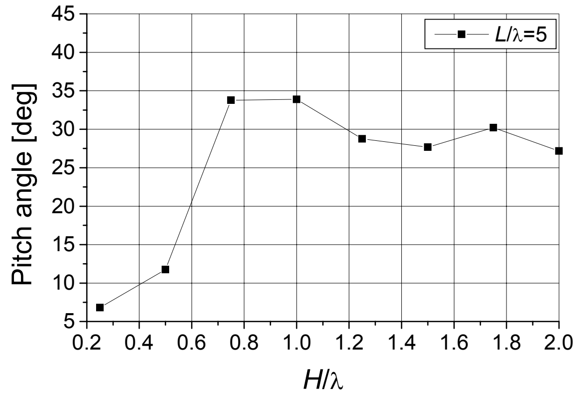

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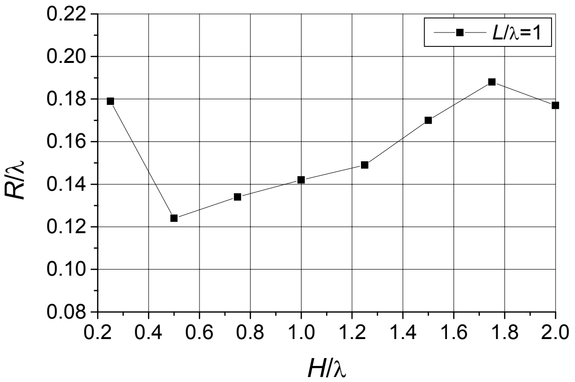
Figure 3. Optimal pitch angle versus normalized truncated-cone height for normalized helix lengths (a) $L/\lambda = 1$, (b) $L/\lambda = 2$, and (c) $L/\lambda = 5$



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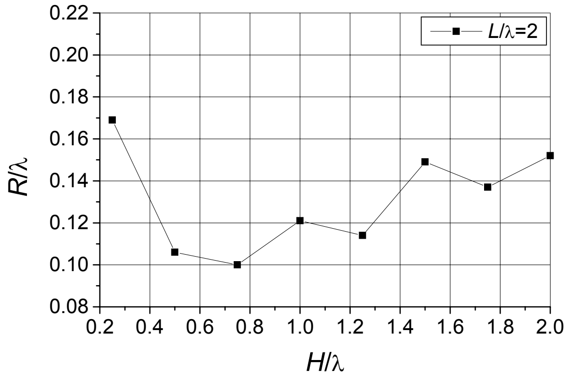

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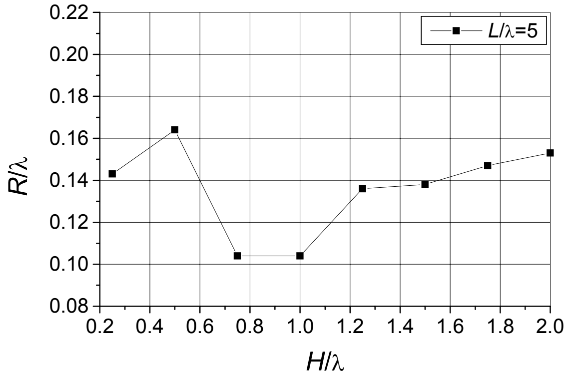
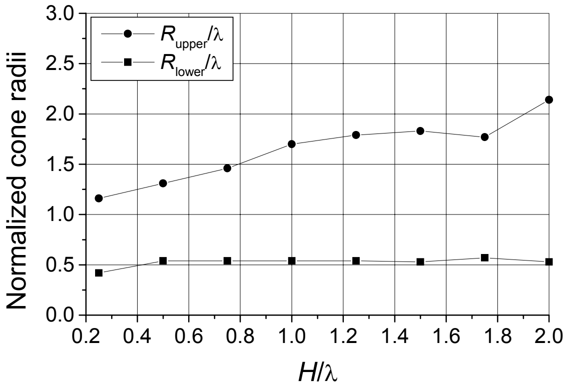


(c)

Figure 4. Optimal normalized helix radius versus normalized truncated-cone height for normalized helix lengths (a) $L/\lambda=1$, (b) $L/\lambda=2$, and (c) $L/\lambda=5$



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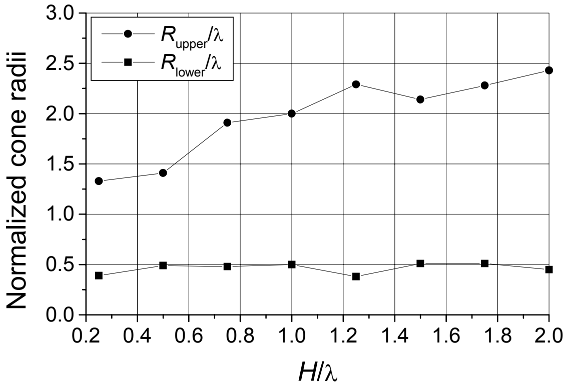

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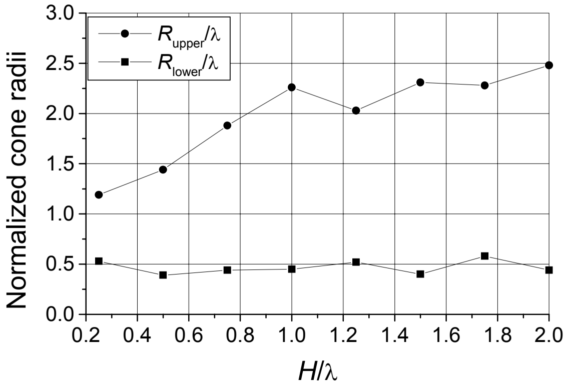

(c)

Figure 5. Optimal normalized upper and lower cone radii versus normalized truncated-cone height for normalized helix lengths (a) $L/\lambda=1$, (b) $L/\lambda=2$, and (c) $L/\lambda=5$

The data presented in this section can be used for design of optimal helical antennas with truncated-cone reflectors. The first step is to select the helix length (L) and the cone height (H) based on the available space and the required gain. This selection is performed by inspecting Fig. 2. The second step is to read the optimal helix pitch angle from Fig. 3, the optimal helix radius from Fig. 4, and the optimal cone radii from Fig. 5.

We would like to point out that the optimal helix dimensions of the antenna with a truncated-cone reflector are different from those of the optimal helical antenna with a flat reflector or a cup reflector, in particular for tall reflectors. For example, the optimal pitch angles for a tall reflector are about 30^{o}, whereas for a flat reflector the optimal angles are several times smaller. Therefore, to obtain the optimal antenna design, the dimensions of the helix and the reflector need to be optimized simultaneously.

It is also worth noting that the truncated-cone reflector has two effects on the helical antenna, and that both effects increase the antenna gain.

First, the truncated-cone acts as a reflector that collects the energy spilled into the sidelobes and directs it upwards.

Second, the reflector has influence on the current distribution along the few lowest turns of the helix. In the classical case of a flat reflector, the current distribution shows a strong standing-wave pattern along the lowest turns. Along the remaining turns, almost all the way up to the top of the helix, the dominant term in the current distribution is a traveling-wave, which propagates along the helix wire (from the feeding point towards the tip). This traveling wave is favorable for obtaining a high gain of the helical antenna.

A reflector that has the form of a cup or a truncated cone enhances the traveling wave distribution along the lowest few turns. An explanation is solicited for this effect. In spite of the influence on the current distribution, the reflector has a small influence on the input impedance of the helix.

4. EXPERIMENTAL VERIFICATION

A helical antenna with a truncated-cone reflector is built. The data used to build the prototype antenna are: helix axial length $L = 684$ mm, helix diameter $2R = 56$ mm, wire diameter $2a = 0.6$ mm, and helix pitch-angle $\alpha = 13.5^{o}$. The operating frequency is 1.7 GHz.

A simple way to verify the influence of the truncated-cone reflector on the performance of the helix is to measure the enhancement of the antenna gain with respect to the gain of the same helix with a square-plate reflector. The gain enhancement is extracted from the following measurement setup. A classical helix antenna is used as a fixed antenna. The power transfer is measured to the helix antenna under test. In one case, the test antenna has a truncated-cone reflector. In another case, the test antenna has a square-plate reflector. The difference of the power transfers (in dB) gives the gain enhancement. The measurements were carried out on a 3 m test range.

Fig. 6 shows the enhancement of the gain of the helical antenna with the truncated-cone reflector ($R_{lower} = 0.75\ \lambda$, $R_{upper} = 2.5\ \lambda$, and $H = 0.5\ \lambda$), with respect to the gain of the same antenna with the square-plate reflector ($b = 1.5\ \lambda$ on a side). The gain enhancement is presented as a function of frequency. The agreement between the computed and measured results is very good [1].

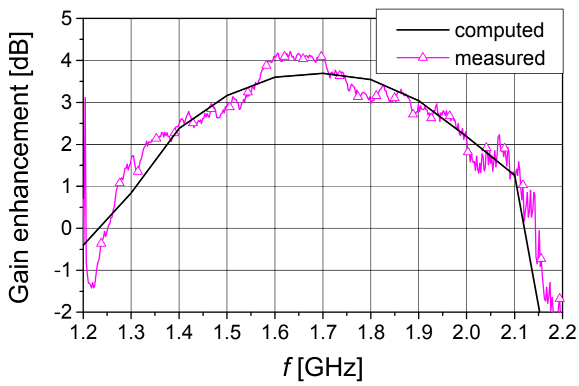

Figure 6. Computed and measured enhancement of helix gain [1]

5. CONCLUSIONS

This paper presented optimization of a helical antenna with a truncated-cone reflector. The optimal dimensions of the helix and the truncated-cone reflector are established using computer simulations. It has been found that the dimensions of the truncated-cone reflector and the dimensions of the helix need to be optimized simultaneously to obtain the optimal design. A set of diagrams is made to enable simple design of helical antennas with truncated-cone reflectors. Furthermore, we have found that the truncated-cone reflector can increase the axial gain of the helical antenna for up to 5 dB for practically realizable sizes of the cone. The results are verified by measurements of a prototype antenna.

The present results are obtained only for one wire radius, for a restricted range of helix lengths, and for narrowband design. Other data sets are in preparation to encompass a wide range of wire radii and longer helices, as well as to cover broadband design.

6. REFERENCES

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