# Impedance Matching of Axial Mode Helical Antennas

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Abstract—In this paper, we study the input impedance characteristics of axial mode helical antennas to find an effective way for matching it to 50 Ω. The study is done on the important matching parameters such as like wire diameter and helix to the ground plane gap. It is intended that these parameters control the matching without detrimentally affecting the radiation pattern. Using transmission line theory, a simple broadband technique is proposed, which is applicable for perfect matching of antennas with similar design parameters. We provide design curves to help to choose the proper dimensions of the matching section based on the antenna's unmatched input impedance. Finally, using the proposed technique, a 4-turn axial mode helix is designed at 2.5 GHz center frequency and the measurement results of the manufactured antenna will be included. This parametric study gives a good insight into the input impedance characteristics of axial mode helical antennas and the proposed impedance matching approach provides a simple, useful method for matching these types of antennas.

Keywords—Antenna, helix, helical, axial mode, wireless power transfer, impedance matching.

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## 1. Introduction

AXIAL mode helical antennas have widely been used for satellite and space communications for a long time having the advantage of circular polarization and wide bandwidth. Novel emerging technologies define new applications for antennas. The microwave wireless power transfer (MWPT) is an example of these emerging technologies which requires high efficiency transmit and or receive antennas with circular polarization in cases where the power is transmitted towards a moving object above the ground. Axial mode helical antennas, designed for a good axial ratio and return loss, are among suitable candidates for such application.

The first comprehensive study of helical antennas was done by Kraus [1] in 1949. Thereafter, other authors proposed new designs like multi-filar [2] and tapered helices [3], and more rigorous studies on the characteristics of these antennas were fulfilled. The effect of important parameters such as the helix pitch angle, circumference, and the number of turns, on the antenna's gain, axial ratio, and bandwidth was also studied. In a few papers, some results on the terminal impedance of these antennas were provided [4]-[6]. Besides, various matching techniques to match the antenna to 50 Ω transmission line were proposed. In some works, quarter wavelength and stub matching techniques were used [7]. Some other approaches such as double-layer metal structure [8], internal wire attachment [9], triangular copper strip [10], and strip incorporated into the first turn [11] have been used in other works. Some of these methods introduce narrowband matching, whereas others are complex utilizing large structures, and in some cases high loss especially in high frequency helices which is critical in efficiency-important applications.

In this work, we study the input impedance of a typical axial mode helical antenna as a function of its wire diameter and spacing from the ground plane to propose a proper matching section. The helix gain, which is dependent on the number of turns and aperture diameter, has been studied sufficiently in the previous literature [12]-[14]. As the terminal impedance of helical antennas do not vary too much as long as the number of turns is more than 4, and for having the proper optimized gain we can choose the number of turns and pitch angle based on the empirical data and formulas provided in the previous works, our main focus is to study the terminal impedance as a function of the wire diameter and its spacing from the ground plane. As mentioned before, in a number of papers some information on the terminal impedance characteristics of the axial mode helical antennas has been given. In this paper, we provide a more complete behavioural treatment on the axial mode helical antenna input impedance. Based on the parametric study of the wire diameter and its spacing from the ground plane, we provide the resistance and reactance curves. Then, we propose a simple single short subwavelength matching section to match the antenna to 50 Ω transmission line. In addition, the design curves for the length and characteristic impedance of the proposed impedance matching section will be provided. The proposed matching approach provides advantages such as simple structure, short length, and broadband matching capability.

## 2. Terminal Impedance Characteristics

We used a 4-turn helix antenna in our study aiming to be used at 2.5 GHz, thus we did the simulations in the 2-3 GHz frequency range to perceive the antenna's impedance behaviour. Using the CST software [12], we calculated the input impedance of the antenna having $13^{\circ}$ winding pitch angle, with the aperture diameter of $3.8\,cm$ positioned on a $12cm \times 12\ cm$ ground plane. The simulations are done for four different wire diameters (D = 1 mm, D = 2 mm, D = 3 mm, D = 4 mm), and at five different wire to ground plane spacings (S = 0.5 mm, S = 1 mm, S = 1.5 mm, S = 2 mm, S = 2.5 mm). The impedance curves are shown in Figs. 1-4. From these results, it is apparent that the imaginary part of the terminal impedance is negative which clarifies it is capacitive. In addition, it is evident that as the wire gets thinner the impedance will become more capacitive. Furthermore, the resistive part of the terminal impedance increases as the wire gets thicker. For all four different helix thicknesses, it can be seen that the reactance lies between -50 Ω to 0 Ω and does not change notably for the same values of helix to ground spacings. Another important observable behaviour from curves is this that the resistive part of terminal impedance increases for thinner wire helices which means they are harder to match comparing to the thicker wire helices. An advantage of the axial mode helical antennas' impedance characteristics is their small impedance variation over a wide frequency range which leads to a wideband capability. Therefore, considering the impedance at the centre frequency of operation to carry out the matching makes it possible to match it to a 50 Ω transmission line over a wide frequency band. In addition, a parametric study was done on the terminal impedance variations as the function of the helix number of turns N. The results are shown in Fig. 5 for N = 4-16. These parametric results, are done for D = 2 mm wire 1 mm above the ground plane. It is obvious from Fig. 5 that the terminal impedance is not too sensitive to the number of turns, which means the drawn curves are helpful for finding the matching dimensions for various helices.

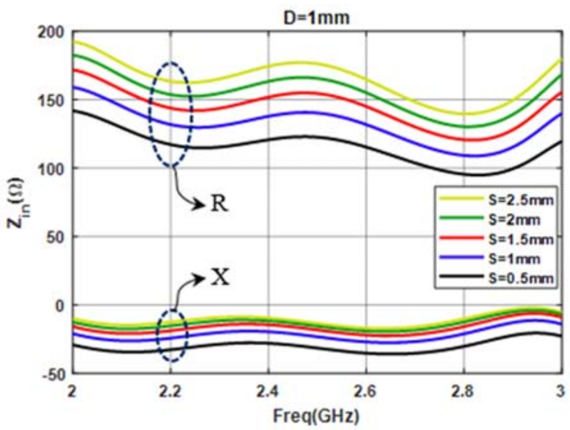


Fig. 1 The 4-turn helix terminal impedance for D = 1 mm over frequency

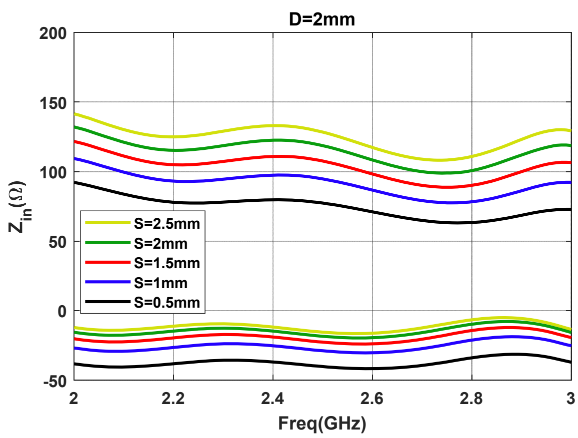


Fig. 2 The 4-turn helix terminal impedance for D = 2 mm over frequency

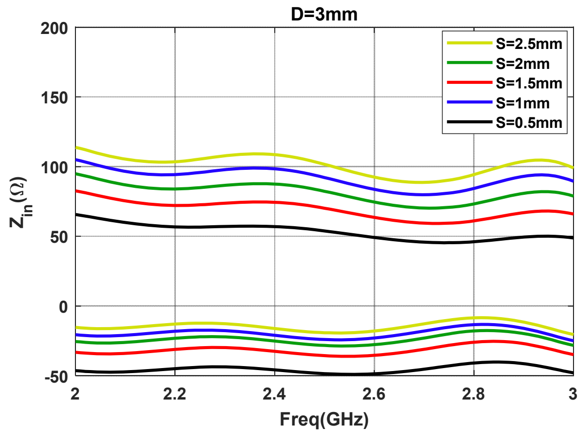


Fig. 3 The 4-turn helix terminal impedance for D = 3mm over frequency

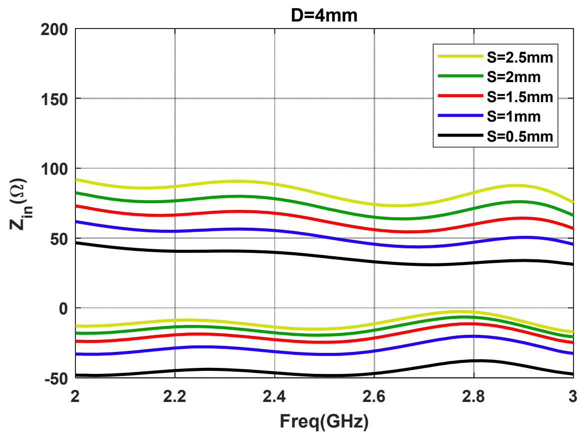


Fig. 4 The 4-turn helix terminal impedance for D = 4 mm over frequency

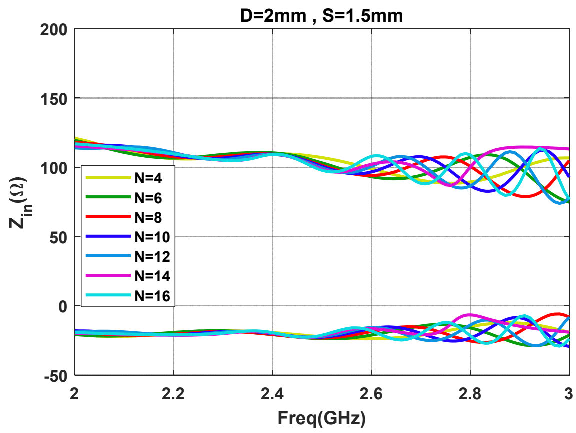


Fig. 5 The terminal impedance of the studied helix for different number of turns

## 3. Antenna Design and Configuration

In this section, we use the basic input impedance calculation formula of a circuit composed of a transmission line terminated to a load that here is the helix over the ground plane. We assume the load impedance as $Z_L = R + jX$ . Here, $Z_L = Z_{in}$ which is indicated in Figs. 1-4.

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tan \beta l}{Z_0 + Z_L \tan \beta l} \quad (1)$$

By substituting $Z_{in} = 50$ in (1), rearranging and separating imaginary and real parts, also considering $C = \tan \beta l$, we derive the following system of equations:

$$\frac{R{Z_0}^2 + RC^2{Z_0}^2}{R^2C^2 + X^2C^2 + {Z_0}^2 - 2XCZ_0} = 50 \quad (2)$$

$$XZ_0 + C{Z_0}^2 - CX^2 - XZ_0C^2 - CR^2 = 0 \quad (3)$$

Supposing that $R$ and $X$ are known, we can solve the equations to find $Z_0$ and $l$. Noting the values of $R$ and $X$ obtained using parametric studies in the previous section, we draw $Z_0$ and $l$ curves for five different values of $X$ over the 50-200 Ω range of $R$. The impedance characteristic of the matching track in terms of $R$ and $X$ is depicted in Fig. 6. It is seen for high values of $R$, $Z_0$ is roughly the same for different values of $X$. Also, it is evident that there is a minimum of $Z_0$ for a special ($R$, $X$) pair value. At this value, the matching track will be the widest one which is suitable for higher powers. The length of matching track in terms of wavelength is depicted in Fig. 7 for the same values of $R$ and $X$ cited before. From this figure, we observe the shorter matching tracks are possible for lower reactance and resistance values. In addition, for a constant value of resistance, the matching track will be shorter when the reactance absolute value is higher, which means a short matching track is possible for a small helix to the ground plane gap. If we use microstrip line, the length of the matching track will become shorter because of lower effective permittivity of the substrate, and accordingly, the shorter guided wavelength.

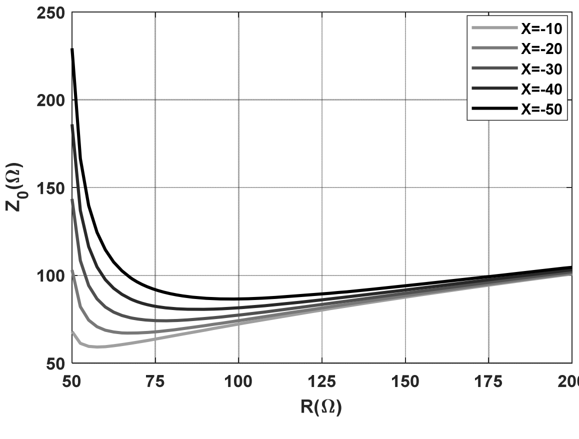


Fig. 6 The length of matching track in terms of wavelength for various values of terminal impedance

A comparison of matching bandwidth capability between open stub and the proposed method was done for the terminal impedance of $Z_l = 60 - 60j$. Fig. 7. shows the locus of the impedance after matching by the proposed method in the Smith Chart for frequency sweep of 0.8-4.5 GHz where the VSWR is lower than two. For the same frequency range, the open stub matching effect on the input impedance is drawn in Fig. 8 which shows that over a large frequency span the impedance lies outside of the VSWR = 2 circle.

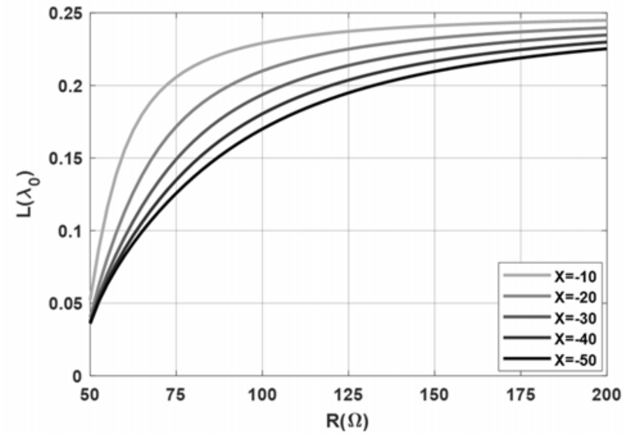


Fig. 7 The characteristic impedance of the matching track for various values of the terminal impedance

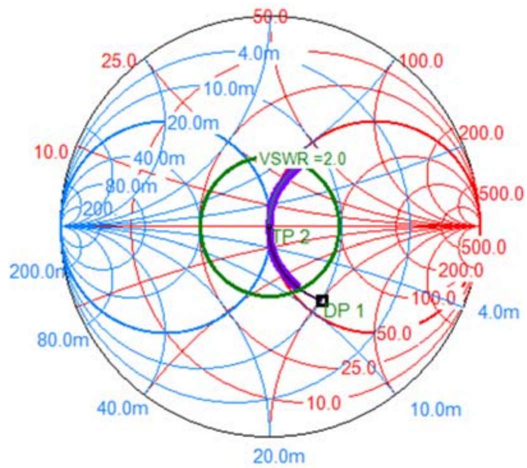


Fig. 8 The matching capability of the proposed matching track on the Smith Chart

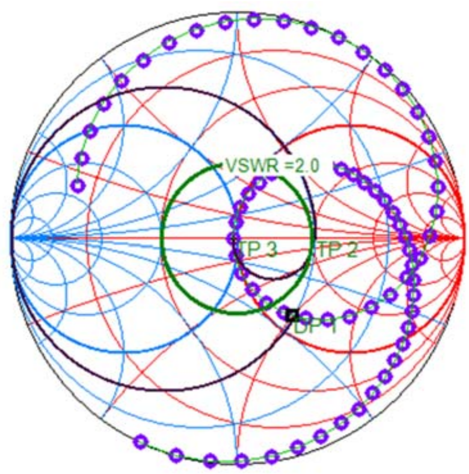


Fig. 9 The matching capability of the open-stub matching section on the Smith Chart

# 4. Manufactured Antenna

The picture of a 4.25-turn manufactured antenna is shown in Fig. 10. A windowed ABS sheet was made using the 3D printer to be used as a support for the proposed helix antenna. The permittivity of ABS filament used for printing is about 3.5. We ought to outline that using any material as the support for the helical antenna will increase the capacitive part in the terminal impedance. This value will be more for higher permittivity and larger supports. The matching track is designed and printed on a Taconic RF-35 substrate with 1.52 mm thickness. The terminal impedance of unmatched helix on the ABS support is $Z_{in} = 62 - 48j$. Using the curves in Figs. 7. and 8, the characteristic impedance and length of the matching line are obtained as $Z_0 = 95\Omega$ and $l = 0.1\lambda$, respectively. Therefore, the length and width of the matching track are equal to $l = 7.5mm$ and $w = 0.98mm$. It should be noted that the guided wavelength conversion should be considered for calculating the track length. The simulated and measured return loss results of the manufactured antenna are included in Fig. 10. A good matching is seen at 2.5 GHz. Also, a large bandwidth (1.62-3.2 GHz) was realized for the manufactured antenna which is about 1 octave. A nearly good similarity is seen between the measured and simulated return loss results from Fig. 11.

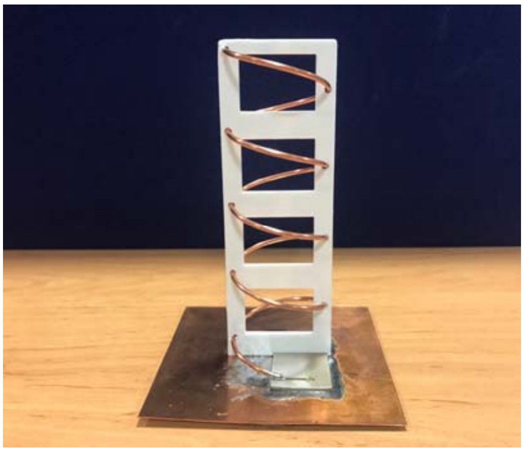

Fig. 10 The manufactured short track matched 4.25-turn helical antenna picture

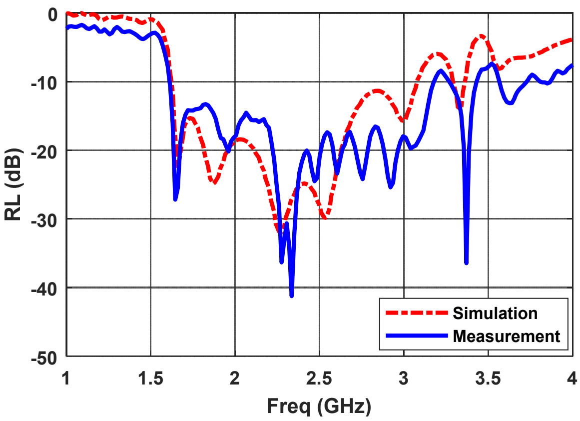


Fig. 11 The manufactured helical antenna's simulation and measured return loss

# 5. Conclusion

In this paper, we studied the helical antenna terminal impedance characteristics as a function of the wire diameter, and the helix to ground plane gap. It was shown that the reactance is capacitive with higher values for the thinner wire. Also, it was shown the resistance part is higher for the thinner wire. We proposed a simple single track matching line to match the antenna to 50 Ω. Based on the transmission line input impedance equation, we drew the matching curves to estimate the length and characteristic impedance of the matching track for various values introduced by the helical antenna. We did a comparison between the proposed and the open stub matching approaches in terms of matching bandwidth capabilities. The proposed matching technique provides a short line, low loss, broadband matching with simple manufacturing benefits. The design curves make it easy for designers to find the proper matching line dimensions for their antennas.

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