Chapter 2. The Axial Mode Helix - A Historical Perspective

2.1 Early Helix Development

The first recognition that an interaction between an electron beam and a traveling wave was possible appeared in work by Haeff [1936, 1941] in 1933. In patents filed in that year, Haeff described electron beam deflection tubes, with many of the features of helix traveling wave tubes, that could be used for oscillographs or detectors. In Haeff's devices, an RF signal propagating along a helical winding was used to deflect a nearby electron beam. This occurs through interaction between the fields produced by the RF signal propagating on the helix and the electrons in the electron beam. There is no indication that Haeff was able to produce amplification.

In 1940, Lindenblad [1942] filed a patent that described a helix traveling wave amplifier similar to the helix traveling wave tube. In Lindenblad's amplifier, the signal was applied to the beam using a grid in the electron gun. Later applications applied the RF signal to the helix. He was the first to explain how synchronous interaction between an electron beam and an RF signal on a helix could produce amplification.

Kompfner at Birmingham University, apparently unaware of Lindenblad's work, developed the first traveling wave tube (TWT) in 1943 [Gittins, 1965]. His goal was to produce an amplifier with sensitivity and noise figure comparable to the best state-of-the-art crystal mixer receivers at the time. Because of war secrecy, his work was not published until 1946 [Kompfner, 1946]. The first public presentation of the British wartime work occurred at the Fourth Institute of Radio Engineer's Electron Tube Conference at Yale University, June 27-28, 1946.

At the same conference work by J. R. Pierce and L.M. Field of Bell Labs was also presented. Later work by Pierce and Field would produce refinements to the TWT that would make it a more efficient and practical device. The small signal theory of the TWT was developed by Pierce and published in 1947 in ***Proc. I.R.E.*** [Pierce and Field, 1947]. Pierce's book ***Traveling Wave Tubes*** [Pierce, 1950], published in 1950, is considered to be the standard reference in the field.

2.1.1 Helical Structures in Traveling Wave Tubes

The traveling wave tube (TWT) is a type of microwave device known as a linear beam tube. There are two dominate types of TWT structures: helix and cavity coupled. The helix TWT uses a helical structure to interact with an electron beam directed down the helix axis, and is of primary interest here. Figure 2.1 [Gilmour, 1994] shows the basic structure of a helix TWT.

In order to explain the interactions between the electron beam and the RF signal on the helix, it is useful to consider a single-wire transmission line over a ground plane as shown in Figure 2.2 [Gilmour, 1994]. The instantaneous RF charges and electric field patterns of the single wire transmission line are shown in Figure 2.2. The RF magnetic field reacts only very weakly with the electron beam, so it is not considered. Assuming an infinitely long lossless line and a generator on the left of Figure 2.2, then the charges and fields shown travel from left to right with a constant amplitude. The velocity of propagation is equal to the speed of light and independent of frequency, i.e. the transmission line is non-dispersive.

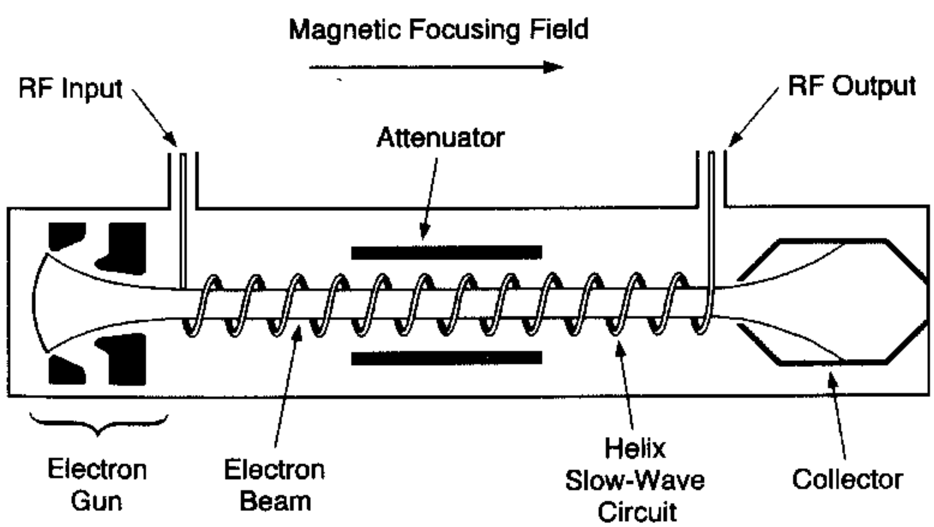


Figure 2.1 Basic helix traveling wave tube amplifier. Reprinted with permission from Principles of Traveling Wave Tubes, by A. S. Gilmour, Jr., Artech House Publishers, Norwood, MA, USA. www.artechhouse.com [Gilmour, 1994]

Now, if the single-wire transmission line is formed into a helix with a circumference much smaller than a wavelength, as shown in Figure 2.3 [Gilmour, 1994], then the RF signal will travel along the helix at a velocity nearly the speed of light. The axial velocity of the RF signal in the helix axis direction will be reduced by an amount equal to the helix pitch angle, creating a slow wave structure. The primary difference between the fields of the single-wire and helix transmission lines is that the helical line has a large axial component of the electric field along the helix axis.

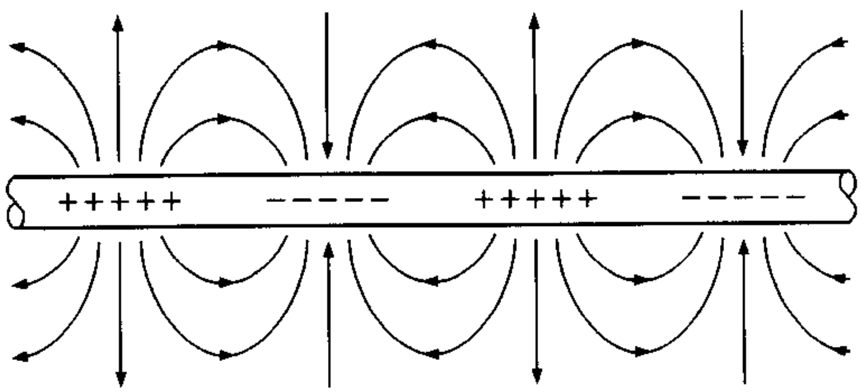


Figure 2.2 RF charge (+ and -) and electric field patterns (solid lines) for a single-wire transmission line above a ground plane. Reprinted with permission from Principles of Traveling Wave Tubes, by A. S. Gilmour, Jr., Artech House Publishers, Norwood, MA, USA. www.artechhouse.com [Gilmour, 1994]

When an electron beam is injected along the helix axis, electrons will be accelerated or decelerated depending upon which part of the axial electric field they interact with. For example, electrons will be accelerated toward the regions marked A in Figure 2.3 [Gilmour, 1994] and decelerated toward the regions marked B. The result is that an electron bunch will form around the regions marked A. This effect is called velocity modulation. The bunching of electrons in the electron beam will in turn interact with the electrons in the RF current flowing along the helix causing them to be repelled. If the velocity of the electron beam and the axial velocity of the helix current are the same, a synchronous interaction between helix current and electron beam current occurs which results in an exponential growth of the circuit voltage [Gilmour, 1994]. The result is amplification of the driving signal as it progresses along the helix. This occurs due to the transfer of energy from the electrons to the wave associated with the RF signal.

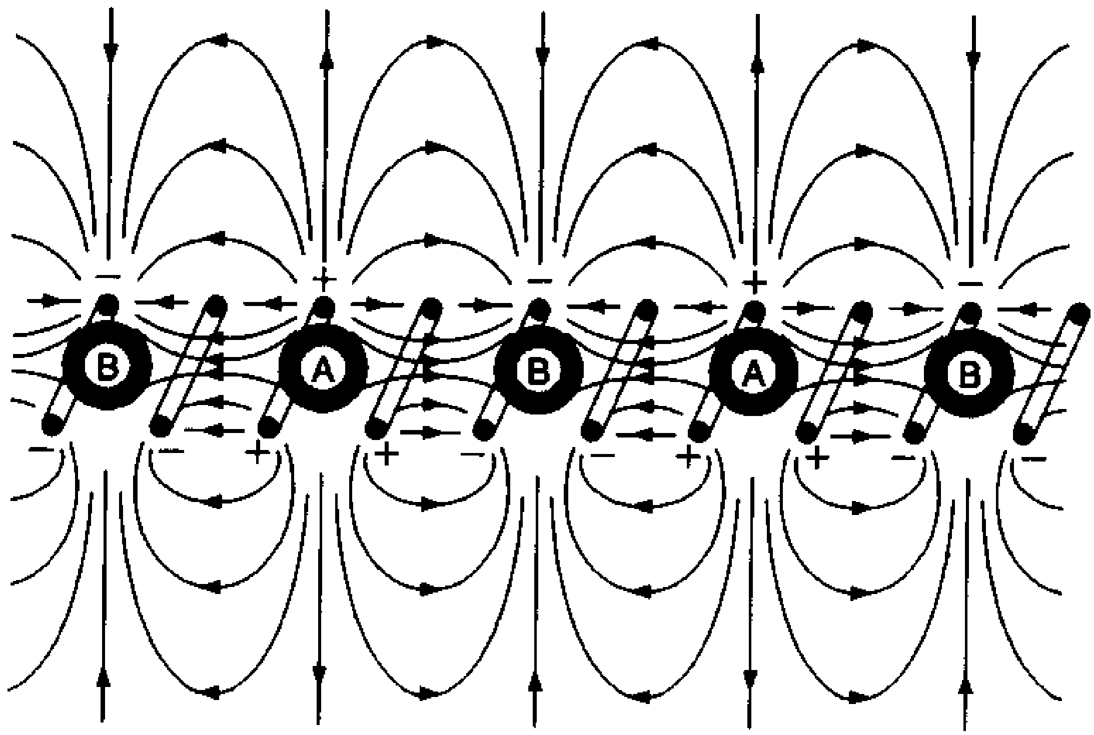


Figure 2.3. RF charge and electric field patterns for a helix. Reprinted with permission from Principles of Traveling Wave Tubes, by A. S. Gilmour, Jr., Artech House Publishers, Norwood, MA, USA. www.artechhouse.com [Gilmour, 1994]

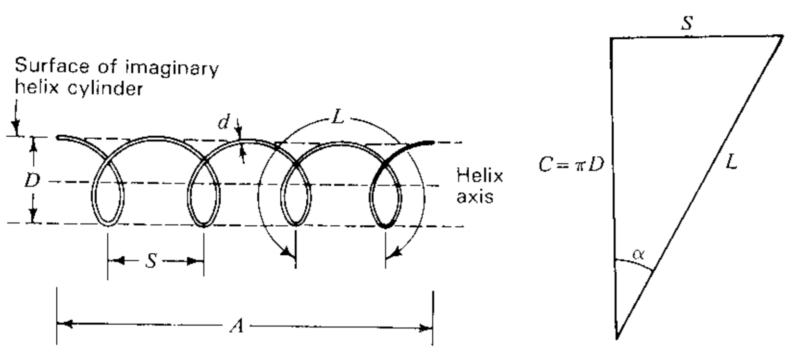
2.1.2 Development of the Helical Antenna

Shortly after the Electron Tube Conference at Yale University, Dr. Paul Raines visited Ohio State University in November 1946 and gave a lecture on traveling wave tube amplifiers [Kraus, 1976]. Dr. John Kraus, an OSU professor, was in attendance. After the lecture Kraus spoke with Raines and asked him if he thought the helix might be made to operate as an antenna. Raines responded that he had tried and the helix would not work as an antenna.

Kraus surmised that the helix may not have worked because it was too small in diameter. Kraus, using a 2.5 GHz oscillator as a source, wound a 7-turn helix with a 4 cm diameter, making for a circumference of 12.5 cm, approximately one wavelength at the source frequency of 2.5 GHz. Using a crystal detector attached to a small fan dipole as a receiving antenna, Kraus was able to verify that his helix produced endfire radiation along the axis of the helix and that the radiation was circularly polarized. This began an exhaustive program of research by Kraus into the properties of the endfire, or axial mode, helix.

The first published work on the helical antenna was in 1947 [Kraus, 1947]. Since then hundreds of papers have been published on the helical antenna detailing the theory of operation, modifications to improve its performance, and variations on the basic helix design. One source exploring many of the helix variations and their performance characteristics is the excellent book by Nakano [1987] which also includes an extensive list of references to other sources.

Figure 2.4 shows the basic geometry of a helical antenna as defined by Kraus [1988]. The defining parameters of the conventional helix are the helix diameter, D, the helix circumference, C, the turn-to-turn spacing, S, the pitch angle of the turns, α, and the axial length, A. The diameter, and hence circumference, primarily determine the frequency of operation of the helix. The circumference of the helix is approximately equal to the wavelength of the center frequency of operation of the helix. The pitch angle and axial length of the helix affect the gain. There is a range of pitch angles which correspond to optimum gain for a given axial length. The longer the axial length, the greater the forward gain of the helix. However, like most traveling wave structures, a point of diminishing returns on gain improvement with length is reached fairly quickly.



(a) (b)

Figure 2.4 Basic helix geometry defining diameter (D), turn-to-turn spacing (S), axial length (A), circumference (C), turn length (L), and pitch angle (α). In (b) the relationships between S, C, D, L and α are shown for a single turn that has been stretched out flat. [Kraus, 1988]

2.2 Variations on the Helix Antenna

The axial mode helix in the form discovered by Kraus was the starting point for many different kinds of traveling wave antennas. This section reviews some of the more prominent ones.

2.2.1 Quadrifilar Helix

The quadrifilar helix antenna, sometimes referred to as a volute antenna, consists of four helical windings oriented 90° with respect to one another, as shown in Figure 2.5. The basic quadrifilar helix, developed by Kilgus [1968, 1969, 1970, 1975], is a unique and versatile antenna. By proper selection of the helix parameters, a wide range of radiation pattern characteristics can be are obtained and good circular polarization can be achieved over a large percentage of the pattern. Although it is commonly used as a spacecraft antenna, the quadrifilar helix can also make an excellent ground station antenna.

The most common configuration of the quadrifilar helix is the half-turn, resonant quadrifilar, as shown in Figure 2.5. This configuration is instructive in understanding the operation of the quadrifilar. Quadrifilar helices are often confused with the more common conventional helix antenna, most likely due to the helical shape of the windings of both antennas. But the there are critical physical and electrical differences between the two.

The conventional helix consists of one, and occasionally more, helical windings, usually with multiple turns. The windings are usually fed in-phase. Their circumference is approximately one-wavelength at the operating frequency and typically have pitch angles (measured from turn-to-turn) of 10° to 15°. The axial mode of operation is supporting a traveling wave along the helical winding to produce an endfire radiation pattern. The conventional helix is usually fed against a groundplane, typically at least one-quarter wavelength in diameter.

The quadrifilar helix consists of four helical windings, spaced 90° with respect to the adjacent winding, enclosing a common volume. The opposing windings are usually joined to form a pair of orthogonal bifilar helices. The windings are fed in phase quadrature between adjacent windings. Besides the phasing, the most significant differences between the conventional helix and the quadrifilar helix are the helix diameter and pitch angle.

Depending on the desired pattern characteristics, the diameter and pitch angle of the quadrifilar windings can vary over a relatively large range. But generally, the diameter is much smaller and its pitch angle is large in comparison to the conventional helix.

For short quadrifilar helices (one turn or less) the radiation pattern is essentially endfire, but is very broad. Half-power beamwidths of greater than 90° are typical, and good circular polarization over a very large percentage of the pattern is expected. As the number of turns on a quadrifilar is increased, the pattern becomes more broadside with the beam peak moving toward the horizon and the beamwidth becomes narrower. As this occurs, the peak gain increases, but the portion of the pattern over which good circular polarization is produced narrows, but is usually located around the beam peak. Omnidirectional azimuthal coverage is maintained in all of these configurations. Figure 2.6 illustrates the change in elevation pattern as the number of turns of the quadrifilar increases.

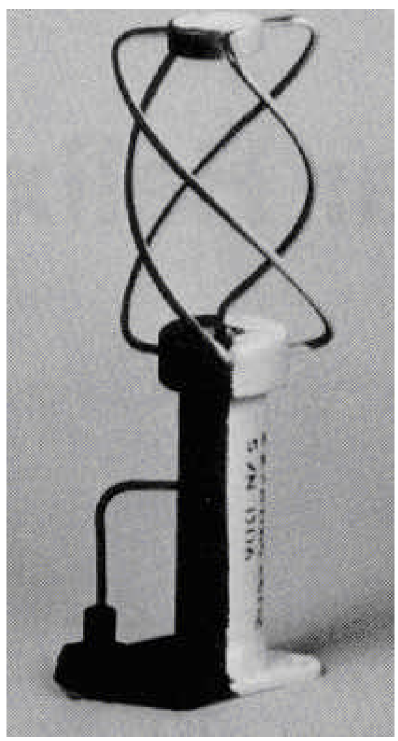


Figure 2.5. Typical quadrifilar helix or volute antenna [Maxwell, 1990]

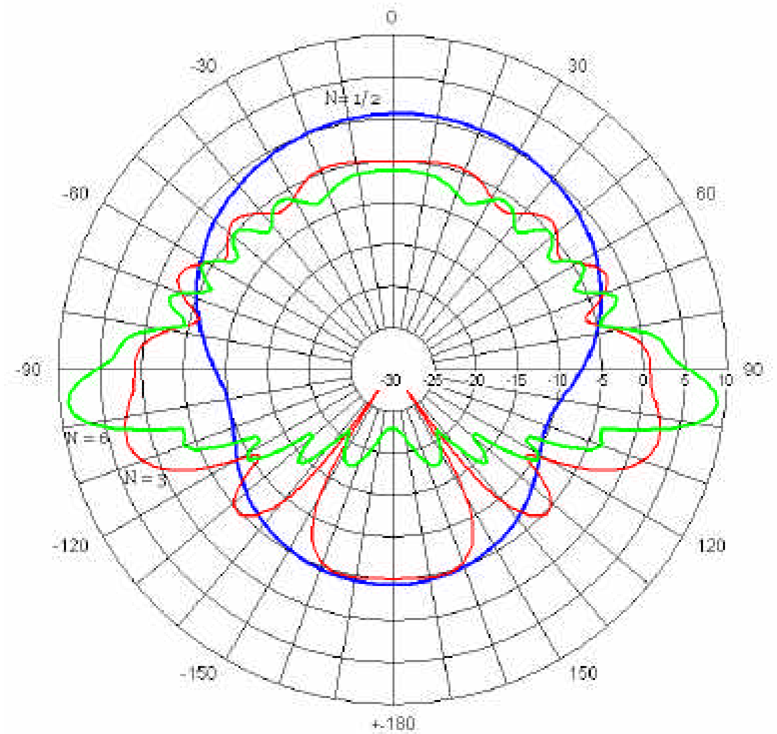


Figure 2.6 NEC simulated radiation patterns of quadrifilar helices with N = 1/2, N = 3, and N = 6 turns showing how the main lobe of the pattern moves from on-axis to broadside of the quadrifilar as the number of turns is increased. The helix axis is aligned with $\theta = 0°$, the same orientation as in Figure 2.5.

2.2.2 Spherical Helix

The traditional helix antenna consists of a helical winding on a cylindrical surface. Safaai-Jazi and Cardoso [1996] proposed a helical antenna that is formed on a spherical surface. The spherical helix consists of a helical winding with constant spacing between turns formed on a spherical surface. Their study indicated that the spherical helix has some interesting properties that are distinctly different from conventional helices.

Over the range where the circumference of the sphere is $0.75\lambda < C < 2.0\lambda$, the spherical helix radiates in an endfire mode producing circular polarization. The gain of the antenna does not vary significantly with the number of turns used, unlike a cylindrical helix. While at first this may be a surprising result, it should not be since, regardless of the number of turns used, the volume of the antenna is being held constant. The on-axis gain of the sperical helix operating over this frequency range was measured as 9 dB with 3 dB and 10 dB beamwidths of 60° and 110°, respectively. The axial mode circumference range of $0.75\lambda < C < 2.0\lambda$ corresponds to an bandwidth of approximately 91%.

Over certain narrow ranges within the circumference range cited above, the spherical helix produces circular polarization over a broad beamwidth. Specifically, for 4-turn and 10-turn helices with C = 1.15λ and 1.25λ, respectively, the patterns remained circularly polarized over a beamwidth of approximately 120°. It would appear that the axial ratio performance would define the operational bandwidth of the spherical helix. However, there were no specifics given on its expected axial ratio bandwidth.

When the circumference of the sphere is in the range $2.0\lambda < C < 2.8\lambda$, a null of approximately 10 dB develops in the pattern along the axis of the helix. The maximum gain of the bifurcated main lobe is approximately 7 dB and the beams have 3 dB beamwidths of approximately 33°. The polarization produced in this axial-null mode is generally elliptical, but may be circular over narrow frequency ranges. Again, no specifics were given in [Safaai-Jazi and Cardoso, 1996].

The unique characteristics of the spherical helix suggest that it might be a good candidate for use as a mobile antenna for low earth orbiting (LEO) satellite systems. Circular polarization over a broad beamwidth is a highly desired but sorely lacking characteristic in current antenna designs used in LEO systems.

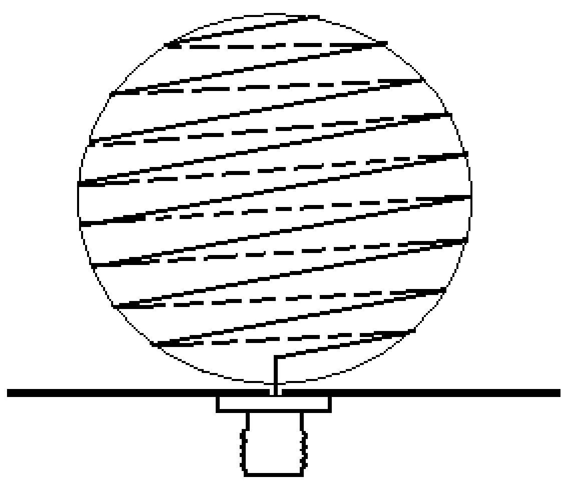


Figure 2.7. Spherical helix antenna with groundplane.

2.2.3 Zig-zag Antenna

Imagine a traditional helical structure that is flattened it into a planar structure. The result would be a wire antenna formed in a zig-zag pattern, see Figure 2.8. Cumming [1955] first investigated this antenna structure followed by Sengupta [1958].

The zig-zag antenna is a form of traveling wave antenna that when properly designed produces a strong axial beam with very low sidelobes. The gain of the antenna is a function of the Vee length (2L in Figure 2.8), the V angle (2α in Figure 2.8), and the number of Vee's. Results reported by Sengupta indicate that zig-zag antenna has a usable bandwidth of approximately 10%, based on the pattern behavior. When the operating frequency is approximately 10% above the center frequency of the antenna, its pattern forms a split beam with a null on axis, similar to an axial mode helix operated in its second mode.

The front-to-back ratio and sidelobe characteristics of the zig-zag antenna are comparable to a Yagi-Uda design of similar length, but with a wider bandwidth due to the traveling wave nature of the antenna. The polarization of the zig-zag antenna is linear, as would be expected of a planar, endfire array. Sengupta's [1958] investigations were prompted by the desire to use the zig-zag antenna in a VHF radiotelescope array being built at the University of Toronto. It appears that this antenna has little other application despite its features of high gain, simple construction, and relatively wide bandwidth.

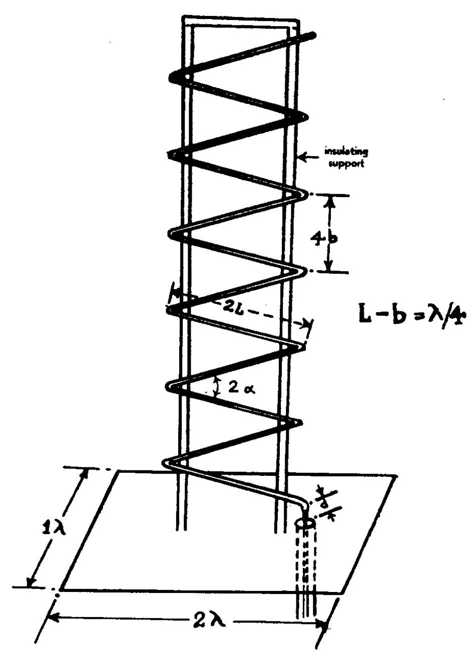


Figure 2.8. Diagram showing the zig-zag antenna with feeding arrangement [Sengupta, 1958]

2.2.4 Helix-Fed Dielectric Rod Antenna

Various attempts have been made to use dielectric loading, usually within the core of an axial mode helix, to reduce the helix size, as shown in Figure 2.9. These attempts have usually met with limited success most likely due to incompatibilities between helical and dielectric antennas. Namely, due to the high permittivity of the dielectric, the electric fields are concentrated within the material, reducing the amount of radiation that occurs.

However, dielectric rod antennas have been shown to produce high directivity when properly designed and fed. Combining a dielectric rod antenna with a small helix as a suitable feed combines the desirable characteristics of both [Hui, et al., 1996]. The helix launches a circularly polarized wave into the dielectric rod which guides and focuses the wave down the rod. Both helix and dielectric rod antenna are slow wave structures, hence there seems to be some basic compatibility in their operation. The result of the combination is a circularly polarized antenna with improved directivity. However, there are no claims of any improvements in gain or in size reduction.

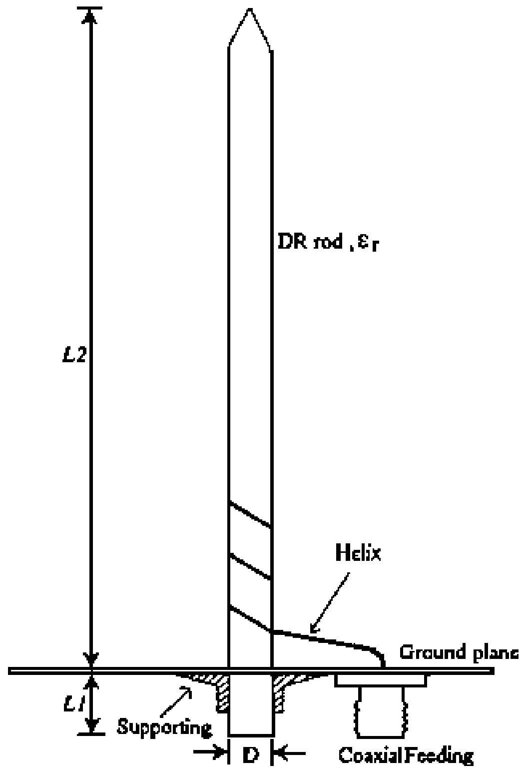


Figure 2.9. Cylindrical dielectric rod antenna fed by a short helix [Hui, et al, 1996]

2.2.5 Internally Matched Helix Antenna

Wong and Chen [1991] presented a design for reduced size variant of the axial mode helix antenna called the internally matched helical beam antenna. The internally matched helical beam antenna shown in Figure 2.10 consists of a helical winding on top of a cylindrical groundplane separated by a thin dielectric layer.

The helical winding over the groundplane forms a transmission line structure. By adjusting the width of the helical winding, the impedance of the transmission line is adjusted to provide a match to 50 Ω allowing direct feed of the antenna. The distributed inductance and capacitance of the transmission line structure result in a velocity of propagation along the winding less than the speed of light. This slow wave structure results in a size reduction for the helix. Wong and Chen claim an 86% reduction in the diameter of the helix using this technique.

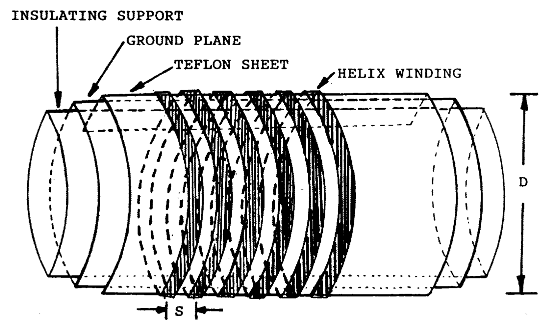


Figure 2.10 The schematic diagram of an internally matched helical antenna; S = spacing between the turns and D = diameter of the helix or the insulating cylinder [Wong and Chen, 1991].

The principle of using a microstrip transmission line structure in order to create an antenna seems counterintuitive. Well designed transmission line structures do not radiate well, as is desired for transmission. Significant radiation usually occurs when either the spacing between the transmission line and groundplane becomes electrically large or the width of the transmission line becomes a significant fraction of a wavelength, as in the case of microstrip patch antennas. The internally matched helix can excite a surface traveling wave along its structure, but one would expect that such a wave would remain tightly coupled to the microstrip structure resulting in low radiation efficiency. Wong and Chen [1991] show radiation patterns for their test antenna which demonstrate directivity, but make no claims about gain. They report an estimated radiation efficiency of more than 70%, but it is not entirely clear how they arrived at this number. An investigation by Spall, et al. [1994] failed to reproduce the results of Wong and Chen. The proposed directivity was observed but gain was very low.

2.2.6 Slow-Wave Helix

Based in part on the idea of the zig-zap spiral antenna, a helix geometry using zig-zag windings was developed by Spall, et al. [1994]. The Slow-Wave helix, shown in Figure 2.11, consists of a helical winding with a regular, evenly spaced zig-zag pattern along the axial direction of the antenna. This antenna design was originated by Spall and Stutzman at Virginia Tech. The zig-zag winding creates a slow wave transmission line structure for the helix. The phase velocity within the winding is lowered resulting in a shorter wavelength within the helix. Initial investigations indicated a diameter size reduction of almost two over a conventional axial mode helix [Spall, et al., 1994].

A later study consisting of an extensive parameter study using numerical modeling revealed some significant limitations to the Slow-Wave helix geometry [Barts and Stutzman, 1996]. The diameter reduction of the Slow-Wave helix was almost a factor of two; additionally, the length was less than one-half that of a conventional helix for the same number of turns. There was, however, a significant reduction in gain compared to a conventional helix. In modeling comparisons between five-turn Slow-Wave and conventional helices, it was observed that the Slow-Wave helix exhibited between 1 and 3 dB less gain than the conventional helix over their range of operation. Additionally, the Slow-Wave helix model exhibited a relatively narrow frequency range over which the axial ratio was low. The 3-dB axial ratio bandwidth was approximately 10%.

The Slow-Wave helix was developed as part of an effort to reduce the size of helical antennas for use in UHF military satellite systems. While it met the size reduction requirements and its gain reduction was tolerable, its limited bandwidth removed it from consideration. The limitations of the Slow-Wave helix were the motivation that led to the development of the Stub Loaded Helix. The Slow-Wave helix still holds promise for applications where moderate bandwidth is acceptable. The previous studies of the Slow-Wave helix were by no means exhaustive. The basic concept seems valid but the geometry requires optimizing in order to achieve maximum performance.

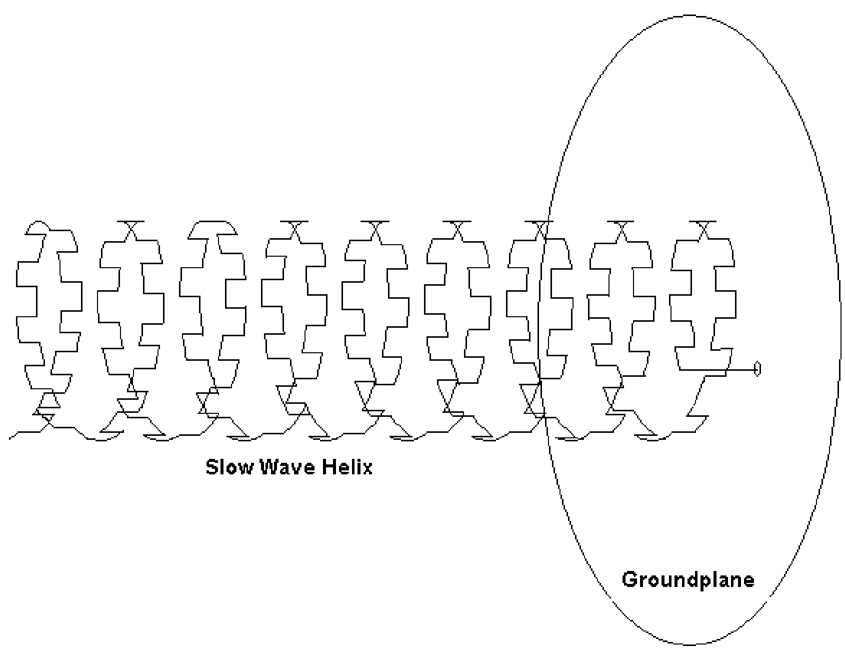


Figure 2.11 Geometry of the Slow-Wave helix

2.2.7 The Helicone Antenna

The helicone antenan is a full size helical antenna placed inside a large cylindrical horn; an example is illustrated in Figure 2.12. The helicone was developed by Carver [1967] as a variation of the helix with extremely low back and sidelobes and increased directivity over a stand alone helix. The helicone's bandwidth and axial ratio properties are superior to those of a conical horn excited from a circularly polarized waveguide operating in the TE_{11} mode. The impedance behavior of the helicone is very similar to that of the helix alone, being predominately resistive with a small amount of reactance across the operating bandwidth. The extremely low back and sidelobe levels of the helicone make it an attractive choice for radio astronomy where noise from the warm earth can increase the antenna noise temperature. Due to the low sidelobe levels, mutual coupling is minimal. Thus, using helicones in an array would be relatively straight forward.

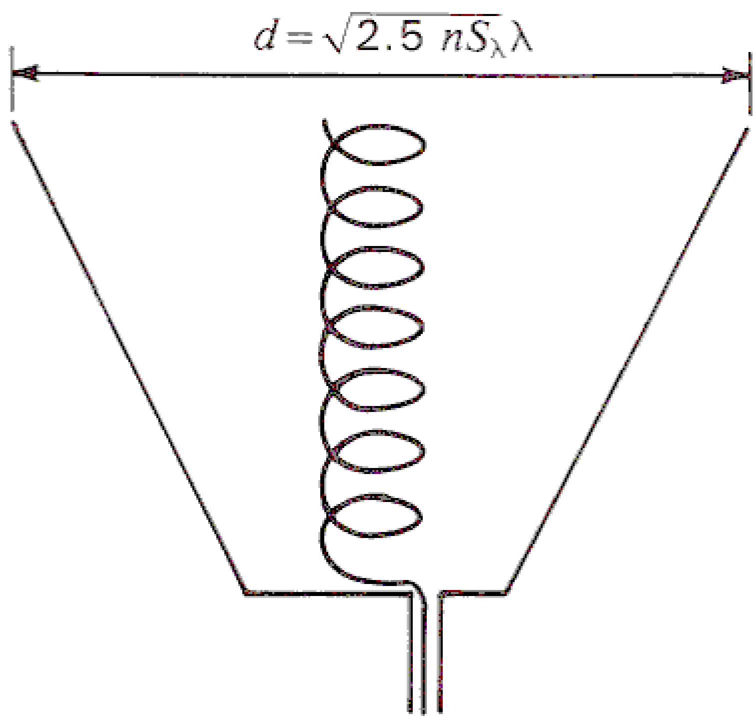


Figure 2.12. The Helicone antenna after Carver [1967]. Image from Kraus [1988].