

Primary frontiers in Designing and benchmarking the Applications of Helical Antennas

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ABSTRACT

Helical antennas are a versatile class of antennas characterized by their spiral-shaped geometry, which enables them to exhibit unique radiation patterns, polarization properties, and frequency characteristics. This comprehensive review explores the design principles, theoretical foundations, and practical applications of helical antennas across various domains, including wireless communication, radar systems, satellite communication, and radio astronomy. By examining the intricacies of helical antenna design, this review aims to elucidate the significance of helical antennas in modern antenna engineering and their implications for advancing wireless communication, sensing, and imaging technologies.

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INTRODUCTION TO HELICAL ANTENNAS

Helical antennas are a type of antenna characterized by their spiral-shaped geometry, which consists of a conductive wire wound into a helix or coil. The helical structure of these antennas imparts unique electromagnetic properties, including circular polarization, wide bandwidth, and high-gain radiation patterns [1]-[23]. Helical antennas find widespread applications in various sectors, including aerospace, defense, telecommunications, and scientific research, owing to their versatility, efficiency, and performance capabilities. Helical antennas are a type of antenna characterized by their helical or spiral-shaped design, which consists of a conducting wire wound in the form of a helix around a central axis. These antennas are widely used in various applications, including satellite communication, radio astronomy, GPS systems, and mobile communications, due to their unique radiation characteristics and compact form factor as in Fig. 1.

The helical structure of these antennas enables them to achieve circular polarization, which is advantageous for communication systems that require robust signal reception in environments with multipath propagation, signal fading, and polarization mismatch. Circularly polarized signals are less susceptible to signal



Fig. 1: Helical antenna

degradation caused by reflection and scattering, making helical antennas well-suited for satellite communication, remote sensing, and GPS applications [24]-[42]. Another key advantage of helical antennas is their broadband performance, with the potential to cover a wide frequency range with a single antenna design. By adjusting the dimensions and parameters of the helix, such as the number of turns, pitch angle, and diameter,

helical antennas can be optimized for specific frequency bands or applications, offering versatility and flexibility in antenna design.

Moreover, helical antennas exhibit directional radiation patterns with high gain, making them suitable for long-range communication and point-to-point links. The directional characteristics of these antennas enable efficient transmission and reception of signals over extended distances, with improved signal-to-noise ratio and coverage area compared to omnidirectional antennas. In summary, helical antennas offer a combination of circular polarization, broadband performance, and directional radiation characteristics, making them well-suited for a wide range of communication and sensing applications. As technology continues to advance, helical antennas are expected to play an increasingly important role in wireless communication systems, satellite networks, and remote sensing platforms, driving innovation and enabling new possibilities in antenna design and deployment [23]-[29].

DESIGN PRINCIPLES OF HELICAL ANTENNAS

- **Helix Geometry:**The geometry of a helical antenna is determined by parameters such as pitch, diameter, and number of turns. The pitch refers to the distance between successive turns of the helix, while the diameter denotes the size of the helix [31]-[39]. The number of turns determines the overall length and resonant frequency of the antenna. By adjusting these parameters, engineers can tailor the radiation characteristics, impedance matching, and operating bandwidth of helical antennas to meet specific application requirements. The geometry of a helical antenna is characterized by its helical or spiral-shaped structure, which consists of a conducting wire wound around a central axis in a helix pattern. The helix geometry is defined by several key parameters, including the number of turns, pitch angle, diameter, and length of the helix as in Fig. 2.



Fig. 2: Helical antenna-II

The number of turns refers to the total count of complete revolutions made by the conducting wire around the central axis of the helix. This parameter determines the overall length and electrical length of the antenna, affecting its resonant frequency and radiation pattern.

The pitch angle, also known as the helix angle, describes the inclination or tilt of the helical turns relative to the central axis. It determines the spacing between adjacent turns and influences the impedance and radiation characteristics of the antenna. The diameter of the helix refers to the size of the circular cross-section formed by the conducting wire. Larger diameters result in wider bandwidth and higher gain, while smaller diameters offer increased mechanical strength and compactness. Finally, the length of the helix corresponds to the total physical length of the conducting wire wound in the helical pattern. This parameter affects the electrical length and resonant frequency of the antenna, determining its operating frequency range and impedance matching characteristics [40]-[51].

Overall, the helix geometry plays a critical role in shaping the electrical and radiation properties of helical antennas, making it essential for optimizing antenna performance and functionality in various applications as in Fig. 3.

- **Radiation Mechanism:**The radiation mechanism of helical antennas is based on the interaction of electromagnetic waves with the helical structure, which causes current to flow along the length of the helix. The helical geometry produces a phased array effect, where electromagnetic waves emitted from different segments of the helix combine constructively or destructively to form a directional radiation pattern. The helical structure also imparts circular polarization to the emitted waves, making helical antennas suitable for applications requiring polarization diversity and immunity to multipath interference. The radiation mechanism of helical antennas is primarily attributed to the current

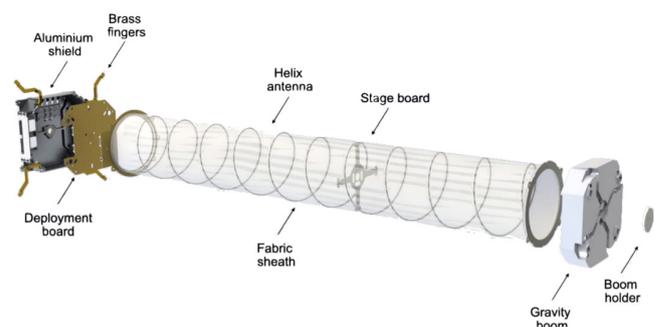


Fig. 3: Design of a Deployable Helix Antenna

flowing along the helix structure. As alternating current passes through the helical conductor, it generates a magnetic field around the wire due to Ampere's law. This magnetic field interacts with the electric field produced by the changing voltage across the antenna, resulting in the emission of electromagnetic waves.

The helix geometry of the antenna influences the radiation pattern and polarization of the emitted waves. Helical antennas are known for their circular polarization characteristics, which are achieved by the combined effects of the helical structure and the phase difference between the currents flowing along the helix [16]. The directionality of the radiation pattern is determined by the length and pitch angle of the helix. Longer helices and smaller pitch angles produce narrower radiation patterns with higher directivity, while shorter helices and larger pitch angles yield broader radiation patterns with lower directivity.

Additionally, the spacing between adjacent turns and the diameter of the helix affect the impedance matching and bandwidth of the antenna. By adjusting these parameters, designers can tailor the radiation characteristics of helical antennas to meet specific application requirements, such as satellite communication, radio astronomy, and mobile communications.

- Feed Mechanism: Helical antennas are typically fed using a coaxial cable or a balun transformer, which connects to the center conductor or one end of the helix. The feed mechanism determines the impedance matching, polarization, and radiation

efficiency of the antenna. Proper feed design is critical for maximizing the performance and gain of helical antennas, as well as ensuring compatibility with transmission lines and RF systems. The feed mechanism of a helical antenna is crucial for efficiently coupling radio frequency (RF) energy to the radiating structure. Helical antennas typically employ either end-fire or broadside feed configurations as in Fig. 4.

In an end-fire feed configuration, the RF signal is fed directly into one end of the helix, typically through a coaxial cable or waveguide. The signal travels along the length of the helix, exciting the antenna's resonant modes and generating electromagnetic radiation. This configuration offers simplicity and ease of integration but may suffer from impedance mismatches and limited bandwidth.

In a broadside feed configuration, the RF signal is applied perpendicular to the helical axis, typically through a balun or matching network. This configuration provides more uniform excitation of the helical structure and can offer improved impedance matching and broader bandwidth compared to end-fire feeding. However, it may require more complex feeding structures and careful impedance matching to achieve optimal performance.

The choice of feed mechanism depends on factors such as desired radiation characteristics, bandwidth requirements, and ease of implementation. Designers must carefully consider these factors when selecting the feed mechanism for helical antennas to ensure optimal performance in their intended applications.

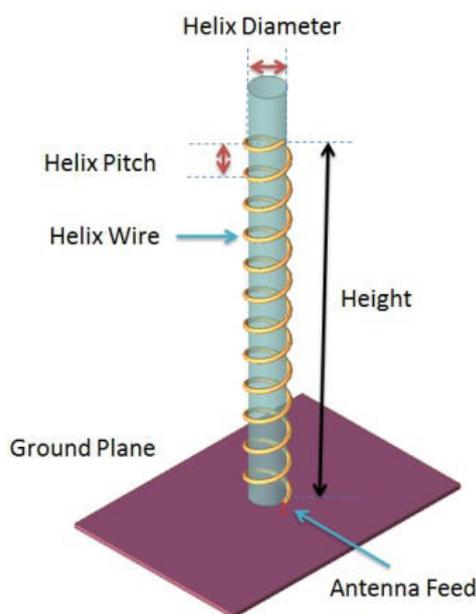


Fig. 4: Helical (Helix) Antenna Design

THEORY OF HELICAL ANTENNAS

-Helical Antenna Theory: The theory of helical antennas is based on electromagnetic principles, including Maxwell's equations, antenna theory, and transmission line theory. The helical structure of the antenna acts as a distributed inductor, storing and radiating electromagnetic energy in the form of electromagnetic waves. The pitch angle of the helix determines the axial radiation pattern, while the diameter and number of turns influence the azimuthal radiation pattern and polarization characteristics. Analytical and numerical methods, such as moment method, finite element method (FEM), and method of moments (MoM), are used to model and analyze the electromagnetic behavior of helical antennas in various operating conditions and environments as in Fig. 5.

- Radiation Patterns: Helical antennas exhibit directional radiation patterns with high-gain characteristics, making them suitable for applications

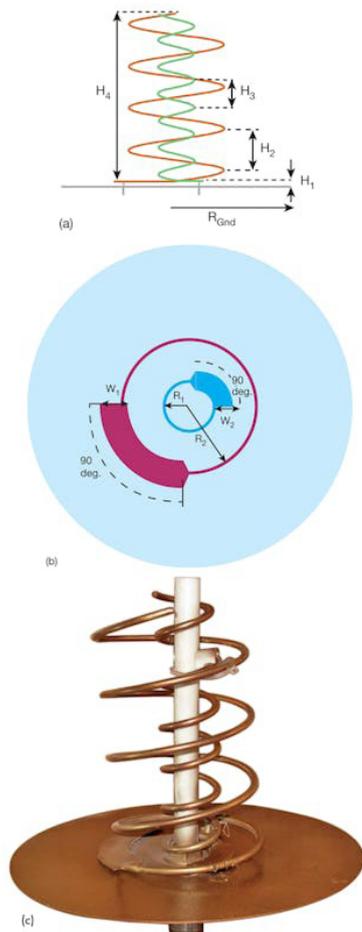


Fig. 5: Helical Antenna Links GSM/UMTS

requiring long-range communication or detection. The radiation pattern of a helical antenna depends on factors such as helix geometry, operating frequency, and feed configuration. The helix acts as a phased array antenna, producing a main lobe in the axial direction and side lobes in the azimuthal direction. By controlling the pitch angle and spacing between turns, engineers can adjust the beamwidth, directivity, and polarization of the radiation pattern to optimize antenna performance for specific applications.

- **Circular Polarization:**One of the key advantages of helical antennas is their ability to generate circularly polarized radiation, which offers advantages in terms of polarization diversity, signal robustness, and interference rejection. Circular polarization is achieved by carefully controlling the helix geometry and feed mechanism to ensure phase and amplitude balance between orthogonal components of the electromagnetic field. Helical antennas with circular polarization are widely used in satellite communication, wireless telemetry, and remote sensing applications, where polarization mismatch and multipath effects are prevalent.

TYPES OF HELICAL ANTENNAS

-**Axial Mode Helical Antennas:**Axial mode helical antennas are characterized by their long, slender helix structure, which produces a predominantly axial radiation pattern with high gain and narrow beamwidth. Axial mode helical antennas are commonly used in satellite communication, radio astronomy, and telemetry systems, where long-distance communication and high-gain reception are required as in Fig. 6.

- **Normal Mode Helical Antennas:**Normal mode helical antennas are characterized by their shorter, wider helix structure, which produces a predominantly azimuthal radiation pattern with omnidirectional or hemispherical coverage. Normal mode helical antennas are commonly used in terrestrial communication, mobile communication, and RFID systems, where wide coverage, circular polarization, and multipath rejection are desired.
- **Quadrifilar Helical Antennas:**Quadrifilar helical antennas consist of four helical arms wound in parallel around a central axis, resulting in a compact, multi-element structure with circular polarization and low axial ratio. Quadrifilar helical antennas are widely used in satellite navigation, GNSS receivers, and remote sensing applications, where robustness to interference, multipath rejection, and global coverage are critical.

APPLICATIONS OF HELICAL ANTENNAS

- **Satellite Communication:**Helical antennas are extensively used in satellite communication systems for transmitting and receiving signals between ground

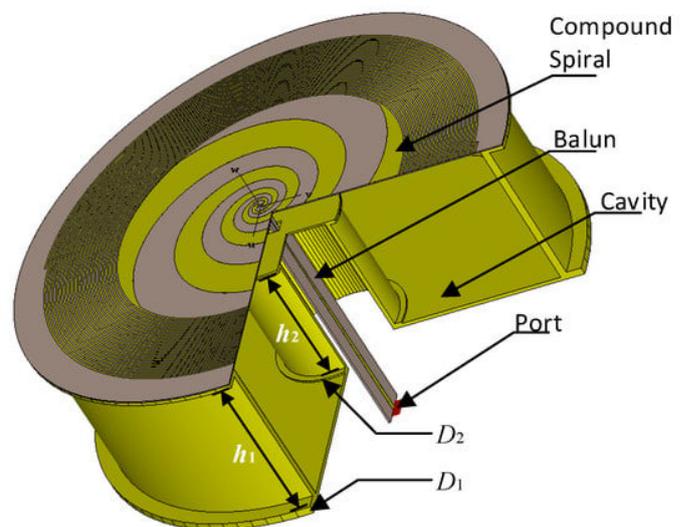


Fig. 6: Ultra-Wideband Low-Cost High-Efficiency Cavity-Backed Compound

stations, spacecraft, and satellites. The high-gain, directional radiation patterns of helical antennas make them ideal for long-range communication links, where signal strength, reliability, and link budget are paramount. Helical antennas are commonly deployed in satellite dish arrays, phased array antennas, and tracking systems for broadcasting, telecommunication, and earth observation applications.

- Radio Astronomy: Helical antennas play a crucial role in radio astronomy for observing celestial objects, galaxies, and cosmic phenomena. The directional, high-gain in Fig. 7.
- Radiation patterns of helical antennas enable astronomers to capture weak radio signals from distant sources with high sensitivity and resolution. Helical antennas are used in radio telescopes, interferometers, and radio interferometry arrays for studying cosmic microwave background radiation, pulsars, quasars, and extraterrestrial signals.
- Wireless Telemetry: Helical antennas are used in wireless telemetry systems for transmitting data, telemetry, and sensor readings in remote monitoring and control applications. The omnidirectional or directional radiation patterns of helical antennas enable reliable communication over long distances, in challenging environments, and in harsh operating conditions. Helical antennas are deployed in environmental monitoring, agriculture, industrial automation, and IoT systems for collecting, transmitting, and analyzing real-time data from sensors, actuators, and IoT devices.
- Radar Systems: Helical antennas are employed in radar systems for detecting, tracking, and imaging

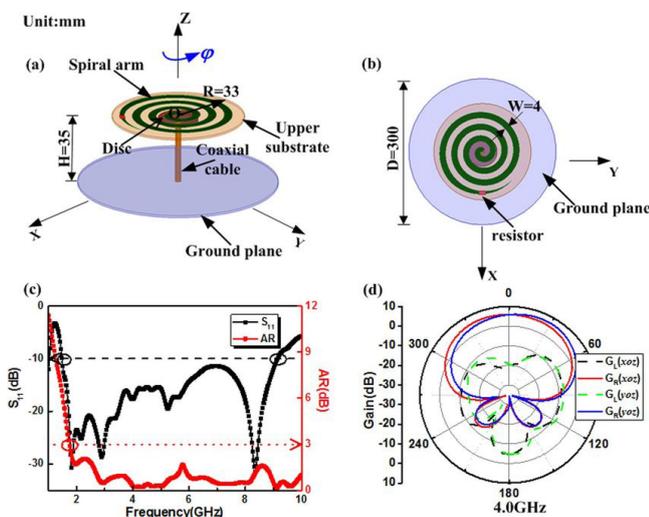


Fig. 7: Geometry and simulated results of the single-arm spiral antenna

targets in air, land, and sea environments. The high-gain, directional radiation patterns of helical antennas enable long-range detection, high-resolution imaging, and target discrimination in radar applications. Helical antennas are used in weather radar, surveillance radar, airborne radar, and military radar systems for detecting aircraft, ships, vehicles, and weather phenomena with high accuracy and reliability.

ADVANCEMENTS AND FUTURE DIRECTIONS

- Miniaturization: Advancements in materials, fabrication techniques, and design methodologies have enabled the miniaturization of helical antennas for compact, portable, and wearable applications. Future research will focus on developing miniaturized helical antennas with reduced size, weight, and power consumption for integration into mobile devices, smart sensors, and IoT platforms.
- Wideband Operation: Helical antennas traditionally operate over a narrow frequency band, limiting their versatility and applicability in multi-band communication systems. Future research will explore techniques for enhancing the bandwidth of helical antennas, such as parasitic elements, frequency-selective surfaces, and metamaterials, to enable wideband operation for broadband communication, cognitive radio, and software-defined radio applications.
- Smart Antenna Systems: Helical antennas can be integrated into smart antenna systems for adaptive beamforming, spatial diversity, and interference mitigation in dynamic and congested wireless environments. Future research will focus on developing smart antenna algorithms, signal processing techniques, and beamforming architectures to optimize the performance of helical antenna arrays for 5G, IoT, and beyond as in Fig. 8.
- 3D Printing and Additive Manufacturing: Advances in 3D printing and additive manufacturing technologies have opened new possibilities for rapid prototyping and custom fabrication of helical antennas with complex geometries and structures. Future research will explore the use of 3D printing techniques to fabricate helical antennas with tailored properties, including

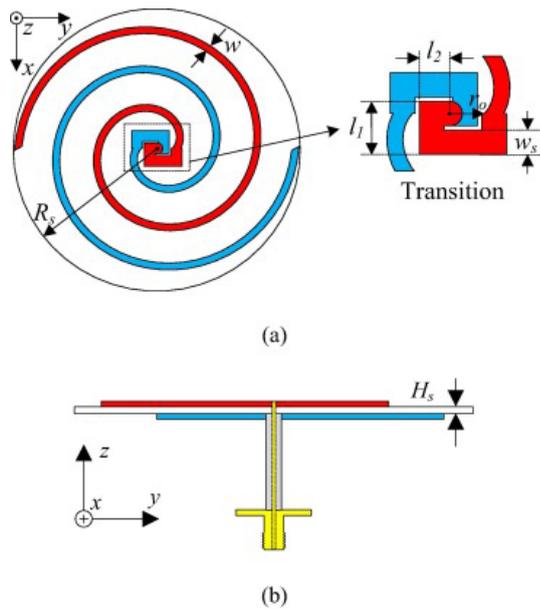


Fig. 8: Ultrawideband, high-gain, high-efficiency, circularly polarized Archimedean spiral antenna

multi-material designs, conformal shapes, and embedded electronics, for applications in aerospace, defense, and medical imaging. 3D printing, also known as additive manufacturing, is a revolutionary technology that enables the creation of three-dimensional objects layer by layer from digital designs. Unlike traditional subtractive manufacturing methods that involve cutting away material from a solid block, 3D printing builds up objects by depositing successive layers of material until the final shape is achieved.

The process begins with the creation of a digital 3D model using computer-aided design (CAD) software or by 3D scanning an existing object. The digital model is then sliced into thin cross-sectional layers, which are sent to the 3D printer for fabrication.

There are several 3D printing technologies available, each utilizing different materials and methods. Common methods include fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and binder jetting. These technologies offer varying degrees of precision, speed, and material compatibility, allowing for the production of a wide range of objects with diverse properties.

3D printing has revolutionized manufacturing processes across industries, enabling rapid prototyping, customized production, and on-demand manufacturing. It has applications in aerospace, automotive, healthcare, consumer goods, and many other sectors, where it is

used to create prototypes, end-use parts, tooling, and even complex geometries that are difficult or impossible to achieve using traditional manufacturing methods. As the technology continues to advance and become more accessible, 3D printing is expected to drive innovation, reshape supply chains, and transform the way products are designed, produced, and distributed.

CONCLUSION

In conclusion, helical antennas represent a versatile and efficient class of antennas with diverse applications in wireless communication, radar systems, satellite communication, and radio astronomy. The spiral-shaped geometry of helical antennas enables them to exhibit unique radiation patterns, polarization properties, and frequency characteristics, making them well-suited for long-range communication, high-gain reception, and circular polarization applications. As wireless technologies continue to evolve and expand, helical antennas will remain an essential component of antenna systems for addressing the growing demand for reliable, high-performance communication solutions. By embracing advancements in design, materials, and fabrication techniques, engineers can unlock the full potential of helical antennas and pave the way for innovations in wireless communication, sensing, and imaging technologies.

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