Ultrawideband Hemispherical Helical Antennas

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***Abstract*—A compact ultrawideband antenna with hemispherical helical geometry is proposed and investigated both theoretically and experimentally. The radiating element of this antenna consists of a tapered metallic strip that assumes a non-conformal orientation relative to the hemispherical surface in order to yield maximum bandwidth. The number of turns is about four and half with a constant spacing between them. The antenna is fed by a coaxial cable with the inner conductor connected to the radiating strip through a matching section, and its outer conductor connected to a ground plane. Radiation properties of the proposed hemispherical helical antenna, including far-field patterns, axial ratio, directivity, input impedance and voltage standing wave ratio (VSWR), are studied numerically and evaluated experimentally. Simulation and measured results are in good agreement. This design provides a maximum directivity of 9±1 dB, a $\mathrm{VSWR} \leq 2$ (relative to a 50 Ω reference impedance), and nearly equal E- and H-plane far-field patterns with high degree of axial symmetry over a bandwidth of more than 50%. Also, over a bandwidth of about 24% the axial ratio remains below 3 dB. The compact size and ultrawideband performance of this antenna make it advantageous for high speed wireless communication systems and avionics.**

***Index Terms*—Hemispherical helical antennas, low profile antennas, spherical helix, ultrawideband antennas.**

I. Introduction

THE spherical helical antenna, first introduced at Virginia Polytechnic Institute and State University, Blacksburg (Virginia Tech), offers some unique advantages, including low profile, compact size, and very broad beamwidth [1], [2]. A modified version of this antenna was later developed by truncating the spherical helix to half of its size to form hemispherical helix that is mechanically more stable. The investigation of the hemispherical helical antenna showed that this geometry, with an optimal number of turns, provides a broader beamwdith over a wider bandwidth and essentially the same directivity as that of the full spherical helix [3]. The radiating elements in both spherical and hemispherical helical antennas in the above studies are thin wires wound over spherical surfaces. These antennas are capable of providing circular polarization, but only over narrow bandwidths. However, much wider bandwidths are required to meet the increasing demands for high data rate information transmission in wireless communication systems. A number of circularly-polarized ultrawideband antenna designs have been reported in recent years [4], [5]. These antennas, while offering more bandwidth, are larger in size and provide several dBs less gain than the hemispherical helix introduced here. Thus, in situations where compact geometry, small size, and light weight are of interest, particularly in aerospace and mobile communication systems, the hemispherical helix would be more desirable.

The study presented in this paper is aimed at exploring new designs for hemispherical helical antennas which can provide ultrawideband radiation characteristics. Attention is focused on introducing new structural designs for the radiating element as well as the feed part of the hemispherical helix in order to increase the overall bandwidth of the antenna to the ultra wideband frequency range. The overall bandwidth here is considered as the frequency range over which axial ratio (AR) is ≤3 dB, VSWR is ≤2, and nearly constant gain and half-power beamwidth are maintained simultaneously. Two modifications over the basic wire design proposed in [3] are introduced, including the replacement of the wire radiating element with a tapered metal strip and the inclusion of a doubly tapered impedance matching section, tapered in both width and height (from the ground plane), that connects the radiating element of the antenna to the feeding coaxial cable.

A comprehensive investigation of the proposed hemispherical helical antenna is carried out numerically as well as experimentally. Radiation characteristics of the antenna including far-field patterns, polarization, input impedance, and directivity are studied. Simulation results are obtained using the commercial software FEKO, suite 5.3 [6]. A prototype of the antenna is constructed and its far-field patterns, gain, VSWR, and axial ratio are measured. In the remaining parts of this paper, design of the radiating element is addressed first. Then, matching of the antenna to a 50 Ω reference impedance is studied. Fabrication of a prototype of the proposed hemispherical helix, measurement of its radiation properties, and comparison of measured and simulation results are discussed.

II. Design of Radiating Element

In a first attempt, the wire radiating element in the basic hemispherical helical antenna design proposed in [3] is replaced with a metal strip. The metal strip may conform to the hemispherical surface or might assume a non-conformal configuration. The numerical analysis of the hemispherical helix with strip radiating element conforming to its surface has indicated that, compared to the basic wire design in [3], very little increase in the bandwidth over which the axial ratio is less than 3 dB can be achieved [7]. On the other hand, hemispherical helices with non-conformal radiating elements as shown in Fig. 1 prove to be much more promising.

For non-conformal strip geometries, it is assumed that the outer edge of the strip resides on the surface of the hemisphere, so that the volume of the hemispherical helix remains

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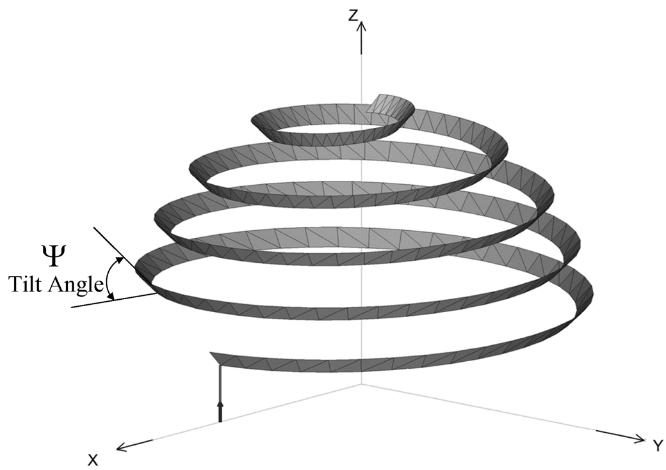

Fig. 1. Geometry of a 4.5-turn hemispherical helical antenna with nonconformal strip radiating element.

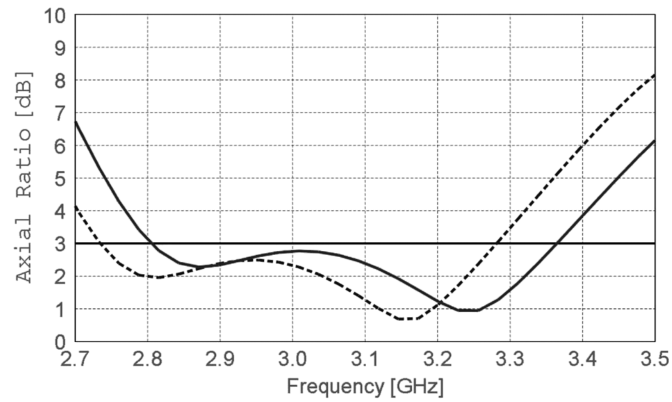

Fig. 2. Variations of axial ratio (AR) versus frequency for hemispherical helical antennas with non-conformal constant-width strip radiating elements and tilt angles $\Psi = 0^\circ$ (——) and $\Psi = 45^\circ$ (......). Both helices have 4.5 turns, radius $a = 20$ mm, strip width $w = 2$ mm, and are side fed by 5 mm short vertical wires.

unchanged and equal to that with the wire radiating element presented in [3]. The geometry of the outer edge of the strip in a spherical coordinate system can be described by the following equations:

$$r = a \tag{1}$$

$$\theta = \cos^{-1}\left(\frac{\phi}{N\pi}\right) \qquad 0 \le \phi \le N\pi \tag{2}$$

where a is the radius of the hemispherical surface encompassing the antenna, and N is the number of turns of the radiating element.

To properly describe the orientation of the non-conformal radiating element we introduce a new parameter referred to as 'tilt angle' (Ψ) and defined as the angle between the ground plane (xy-plane) and a line lying on the strip and perpendicular to its edges. The tilt angle for the geometry shown in Fig. 1 is 45°. The tilt angle may be regarded as a new design parameter that can be adjusted for optimum performance; namely, the widest bandwidth over which the requirements for axial ratio, VSWR, gain, and half-power beamwidth as stated above are met.

The investigation of hemispherical helices with wire radiation elements presented in [3] has shown that the optimal number of turns for achieving maximum axial ratio bandwidth $(\mathrm{AR} \le 3\ \mathrm{dB})$ is about four and half. Our extensive investigation of hemispherical helices with strip radiating elements revealed that the same number of turns provides the widest bandwidth over which the axial ratio is $\le$3 dB. Thus, for all hemispherical helical designs discussed here the number of turns is considered to be 4.5. Variations of axial ratio versus frequency for hemispherical helices with metal strip radiating elements of tilt angles 0° and 45° are depicted in Fig. 2. For both helices the outer radius is $a = 20$ mm and the width of the strip radiating element is $w = 2$ mm. Also, they are side fed by 5 mm vertical short wires as shown in Fig. 1 and infinite ground planes are assumed in their simulations. The results in Fig. 2 clearly indicate that non-conformal radiating element designs indeed increase the axial ratio bandwidth significantly. For example, the design with a tilt angle of 0° provides $\mathrm{AR} \le 3\ \mathrm{dB}$ over a bandwidth of about 18%. Furthermore, comparison of axial ratio results for tilt angles of 0° and 45° in Fig. 2 shows that a left shift in the bandwidth associated with the larger tilt angles occurs. Thus, the tilt angle might be used as a means of fine tuning the frequency range without changing other antenna parameters.

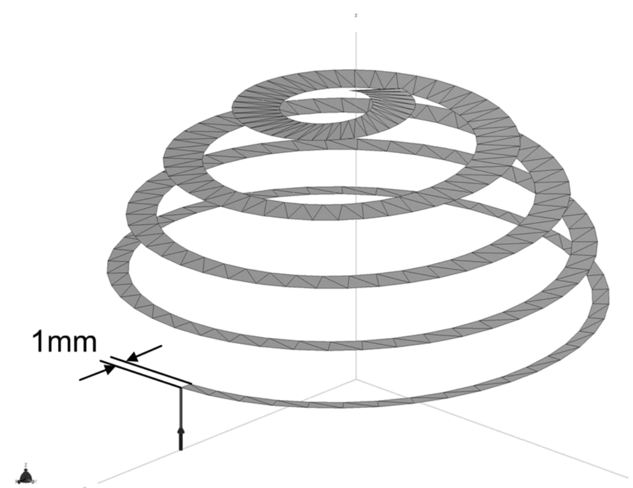

Fig. 3. Hemispherical helical antenna with tapered strip radiating element and tilt angle $\Psi = 0^\circ$.

Next, we consider tapering the strip radiating element, expecting to further increase the bandwidth. It is well known that replacing the wire with a tapered radiating element, as in the case of bowtie antenna, increases the antenna bandwidth [7]. Based on this observation, it is expected that tapering the radiating element shall provide improvements in both the axial ratio bandwidth as well as the bandwidth over which VSWR is $\le$2 (impedance matching is discussed in the next section). Tapering the width of the strip from 1 mm at the feed point to 4 mm at the top of the hemisphere resulted in little change in the axial ratio bandwidth of the conformal design, but for the case of the non-conformal design tapering increased the bandwidth to 20%. Fig. 3 shows the geometry of a hemispherical helix with non-conformal tapered strip radiating element with tilt angle $\Psi = 0^\circ$. Numerical results for the axial ratio of the non-conformal designs with tapered strip with tilt angles 0° and 45° are shown in Fig. 4. Comparison of results in Figs. 2 and 4

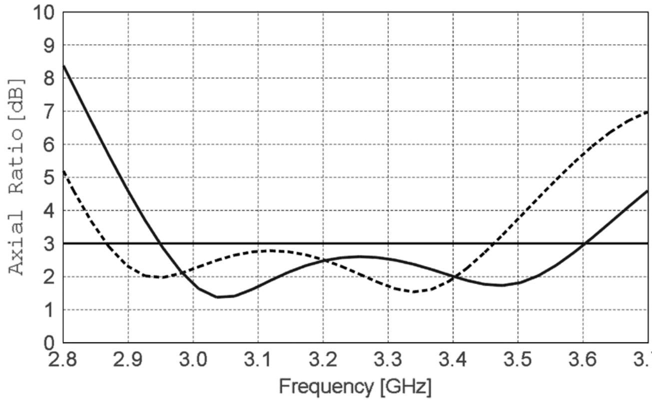

Fig. 4. Variations of axial ratio (AR) versus frequency for hemispherical helical antennas with tapered radiating elements (initial width $= 1$ mm, final width $= 4$ mm) and tilt angles $\Psi = 0°$ (——) and $\Psi = 45°$ (......). Both helices have 4.5 turns, confined to a hemisphere of radius a $= 20$ mm, and are side fed by 5 mm short vertical wires.

indicates that in addition to improving the axial ratio bandwidth, tapering also causes a right shift in the mid-band frequency. This frequency shift is opposite of that due to increasing the tilt angle. Since nonzero tilt angles, as noted in Fig. 4, result in only a small frequency shift, in the remaining parts of this paper only designs with tilt angle $\Psi = 0°$ will be considered.

III. Impedance Matching

In the hemispherical helix design introduced in [3] a horizontal wire parallel to the ground plane is used to connect the feed vertical wire at the center of the hemisphere to the helical radiating wire structure. This horizontal feed wire has some impact on the radiation characteristics of the antenna. Among these characteristics the input impedance is the one affected most, while the directivity, axial ratio, and radiation pattern remain largely unchanged. The feed wire and the ground plane together form a transmission line which can transform the input impedance of the hemispherical helix. On the other hand, if the horizontal feed wire is sufficiently close to the ground plane, due to its opposite image current in the ground plane, it will have negligible impact on radiated fields and thus very little impact on axial ratio and directivity.

One may take advantage of the above mentioned impedance transformation property and try to match the antenna to the signal cable which is considered to have a characteristic impedance of, say, 50 Ω. However, it is desirable that the impedance matching occurs over a wide bandwidth. Tapered transmission lines [8] are known to be capable of wideband impedance transformation. Accordingly, the horizontal wire that connects the feed to the helical wire in the antenna design presented in [3] is replaced with a tapered microstrip line that acts as an impedance matching section. This technique was first implemented on a helical antenna by Kraus [9]. The design of the matching section in this work evolved into its final form after several steps. In a first attempt, we considered an impedance matching section that was a linearly tapered triangular shape microstrip starting from the center of the base of the hemisphere and extending to the radiating element of the hemispherical helical antenna [10]. This matching section is, in fact, a doubly tapered transmission line acting as a wideband impedance transformer. However, simulation results for the antenna of Fig. 3 incorporating such matching section indicated that, while the VSWR bandwidth is improved significantly, the axial ratio bandwidth is decreased slightly.

Since the linearly tapered matching section does not yield a satisfactory increase in the axial ratio bandwidth, we considered a tapered matching section that is closer to the ground plane and

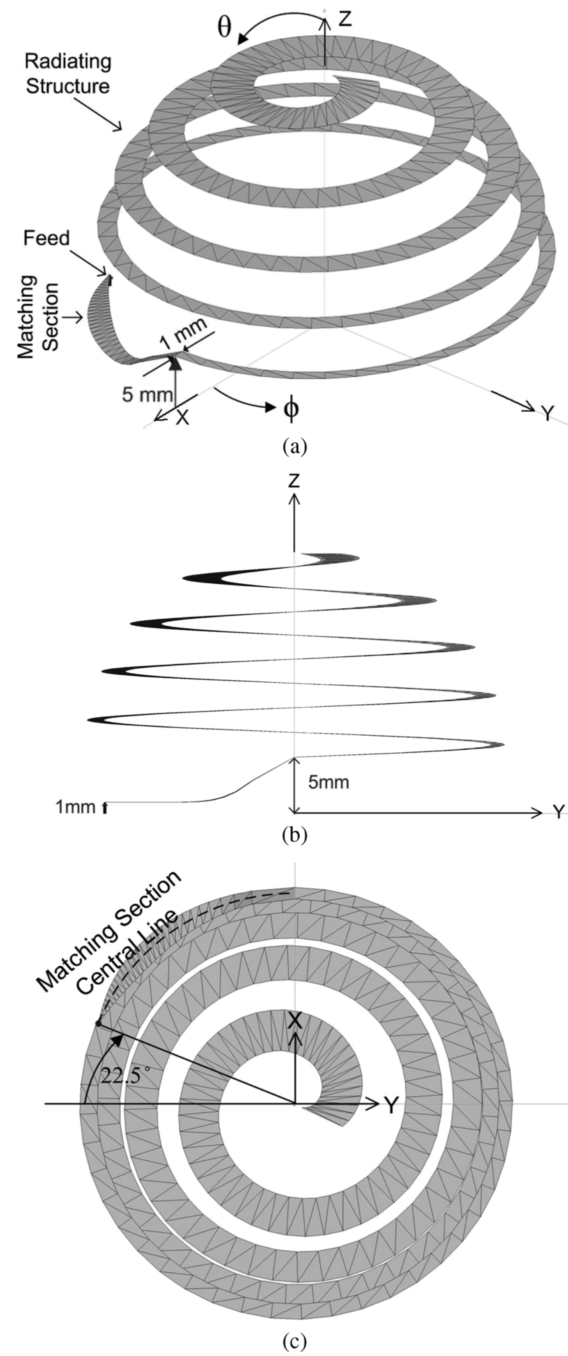

Fig. 5. Geometry of a 4.5-turn hemispherical helical antenna with tapered radiating element (initial width $= 1$ mm, final width $= 4$ mm) and tilt angle $\Psi = 0°$.The helix is confined to a hemisphere of radius a $= 20$ mm and is side-fed by a nonlinearly tapered matching section. (a) 3-D view, (b) front view, (c) bottom view.

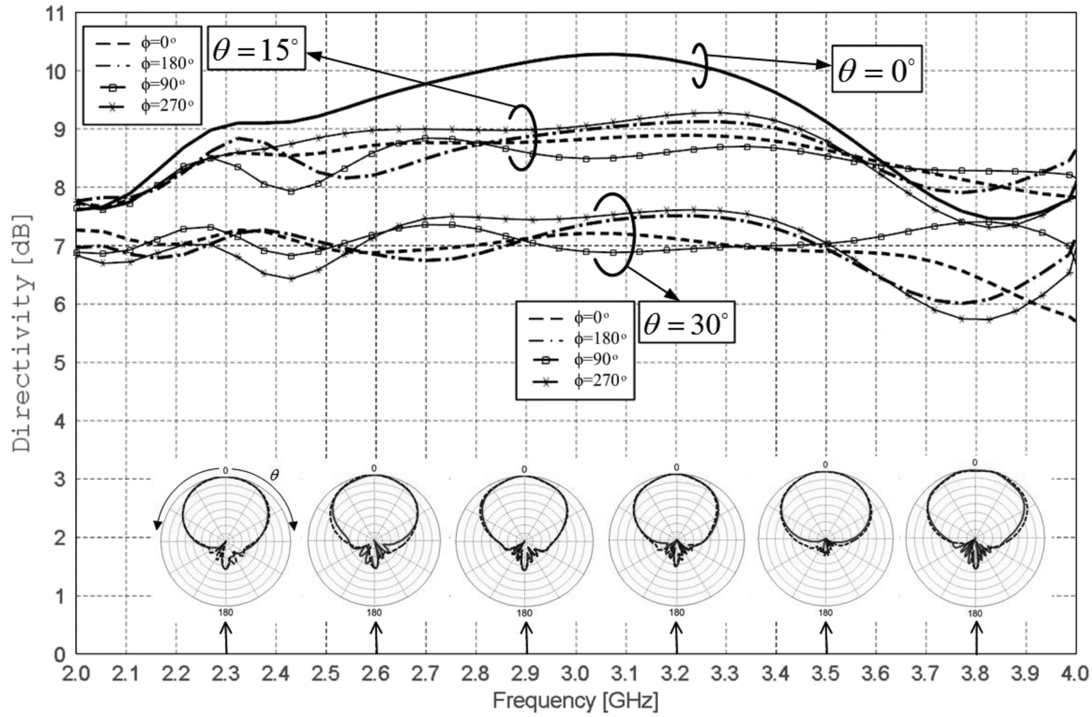

Fig. 6. Variations of directivity versus frequency at several angular directions for the hemispherical helical antenna of Fig. 5. Also shown are normalized power patterns in the xz-plane (——) and yz-plane (. . . . . .) at six different frequencies.

its start point is at the side instead of the center of hemispherical helix. One way to implement this modification is to vary the height of the matching section nonlinearly rather than linearly. This way, a major part of the matching section will remain closer to the ground plane. Furthermore, instead of varying the width of matching section linearly, which leads to abrupt discontinuity or sharp angles at the point of connection to the helix, the width is varied such that connection to the radiating element occurs smoothly, as shown in Fig. 5(a) and (b). The width of this matching section is very small (approximated as zero in simulations) at the start point and is equal to the starting width of the tapered radiating element at the end point. The median curve, that divides the width of the matching section in half, lies on the hemispherical surface as shown in Fig. 5(c). The height of the tapered matching section is 1 mm at the start point and 5 mm at the end point; see Fig. 5(b). A number of different functions were tried for height variations as well as the width of the matching section, and found out that an exponentially varying height and a sinusoidally varying width provide a satisfactory matching performance. By adjusting the exponent of the exponential function, this design permits a major part of the matching section to be very close to the ground plane, thus influencing the radiated fields negligibly.

The hemispherical helical antenna shown in Fig. 5, with its radiating element and impedance matching section now designed for best VSWR and axial ratio performance, was analyzed extensively. The simulation results for directivity and beamwidth of this antenna are presented in the remaining part of this section, while simulation results for axial ratio, VSWR, gain, and far-field patterns are presented and compared with their measured counterparts in the next section. Fig. 6 shows variations of directivity versus frequency along several angular directions. In calculating these results a finite ground plane, equal in size to that used in the constructed prototype (discussed in the next section), is used. It is noted that the maximum directivity at $\theta = 0^\circ$ is about 9 dB with about ± 1 dB fluctuations over a bandwidth of more than 50% (2.2 GHz–3.7 GHz). For $\theta = 15^\circ$ and $\theta = 30^\circ$ the directivity remains relatively constant at about 8.5 dB and 7 dB, respectively, over even a wider bandwidth. The power patterns at six different frequencies in xz- and yz-planes are also presented in Fig. 6. Closer examination of these patterns indicates that each has a broad main beam with a high degree of axial symmetry as manifested by nearly overlapping xz- and yz-plane patterns.

Fig. 7 illustrates variations of the antenna beamwdith in two different plane cuts (xz- and yz- planes) with frequency. The half power beamwidth (HPBW), which measures a 3 dB drop from the maximum directivity, varies between 50° to 80°. For such a broad radiation beam, it is also worth examining the 10-dB beamwdith. This beamwidth remains nearly constant over the entire frequency range, $135^\circ \pm 5^\circ$. It is worth mentioning that, as observed in Fig. 7, there is only about 5° difference between the beamwidths of two different cuts. This property emphasizes the fact that the three-dimensional radiation pattern of the antenna is highly symmetric about the z-axis.

IV. Comparison Between Measured and Simulated Results

A prototype of the design shown in Fig. 5, which yields the maximum overall bandwidth, was fabricated and measured. Measurement results for far-field patterns, axial ratio, VSWR,

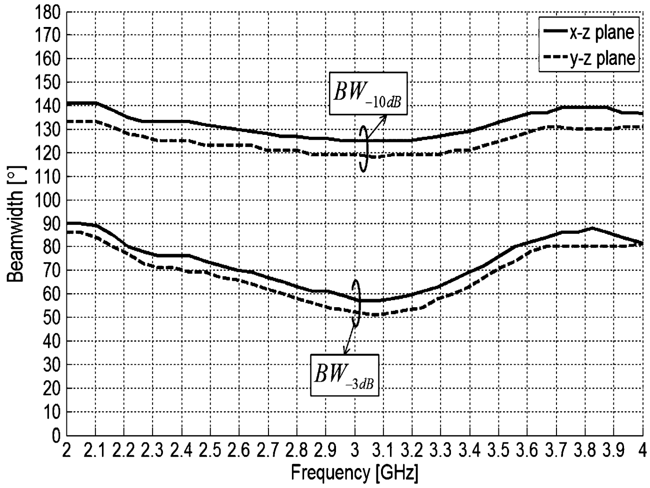

Fig. 7. Variations of 3-dB and 10-dB beamwidths versus frequency for the hemispherical helical antenna of Fig. 5.

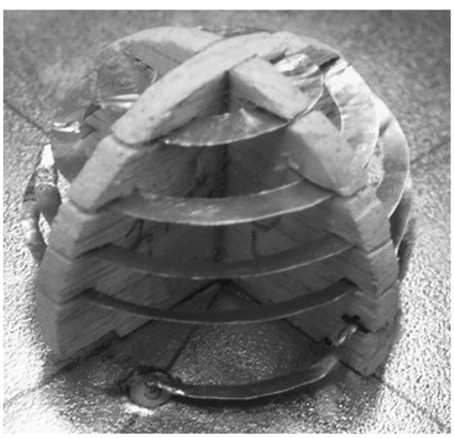

Fig. 8. View of the constructed prototype of the hemispherical helical antenna. The design parameters are the same as those in Fig. 5.

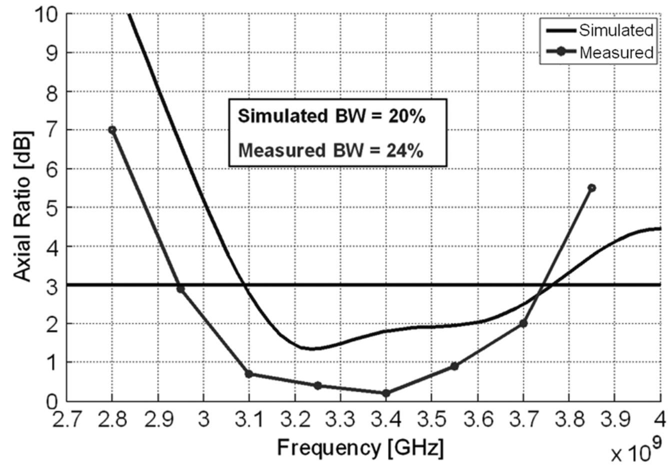

Fig. 9. Comparison of simulated and measured axial ratios for the hemispherical helices shown in Fig. 5 and Fig. 8.

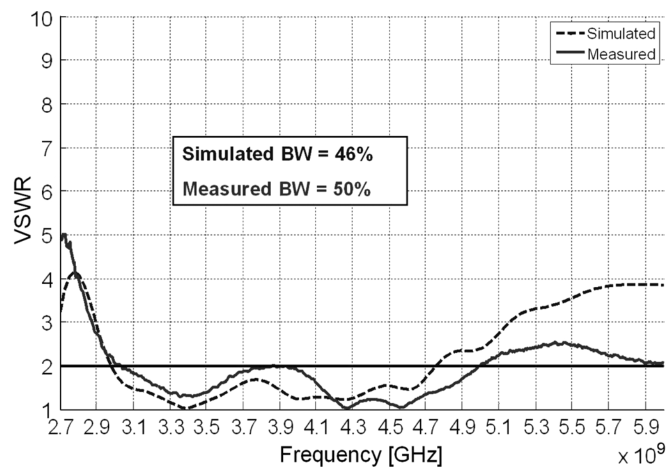

Fig. 10. Comparison of simulated and measured VSWRs for the hemispherical helices shown in Fig. 5 and Fig. 8.

and directivity are presented and compared with the corresponding simulation results in this section. In calculating the simulation results a finite size PEC circular ground plane, with the same diameter as that used in the constructed prototype, is used.

Since the metallic strip used as the radiating element is very thin, a support structure, on which the helix will be mounted, is required. Balsa wood is chosen for this purpose because of its light weight and can be shaped easily. The dielectric properties of Balsa wood do not have considerable impacts on the antenna radiation characteristics. It has a relative permittivity of 1.2 [11]. The constructed prototype is shown in Fig. 8. The assembly of helical strip on support structure and the matching element is mounted on a steel pan which serves as ground plane. Finally, a 50 Ω SMA coaxial connector is attached to the ground plane at the starting point of the matching section. The inner and outer conductors of the SMA connector are soldered to the matching section and the ground plane, respectively. After the prototype was carefully constructed, its radiation characteristics were measured using the facility of the Virginia Tech Antenna Laboratory.

Fig. 9 compares variations of the simulated and measured axial ratios versus frequency for the constructed prototype. There is generally good agreement between the predicted and measured axial ratio results. The measured 3-dB axial ratio bandwidth $(\mathrm{AR} \leq 3\ \mathrm{dB})$ is about 24% relative to a mid-band frequency of 3.35 GHz, while the corresponding simulated bandwidth is about 20% relative to a mid-band frequency of 3.26 GHz. Furthermore, it is noted that the measured AR values are lower than the simulated ones over essentially the entire bandwidth. This might be attributed to the inevitable differences that occur between the actual shape of the radiating element of the constructed prototype and the simulated shape used in calculating its radiation characteristics.

The simulated and measured results for the VSWR of the prototype antenna are presented in Fig. 10. Again, good agreement between the measured and calculated results is noted. The measured VSWR bandwidth $(\mathrm{VSWR} \leq 2)$ is about 50% relative to a mid-band frequency of 4.05 GHz, while the corresponding simulated bandwidth is more than 46% relative to a mid-band frequency of 3.86 GHz. Such a large VSWR bandwidth clearly

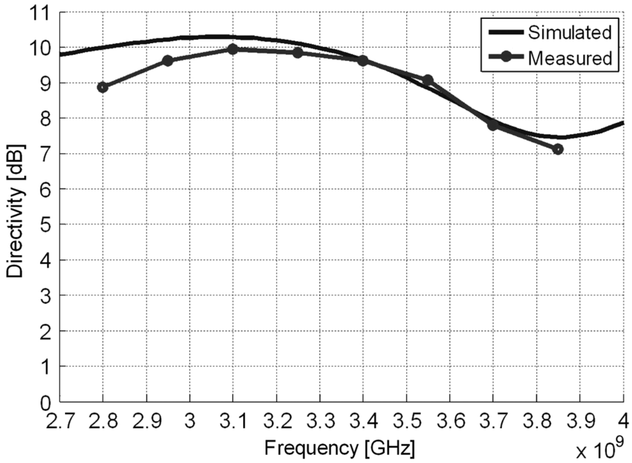

Fig. 11. Comparison of simulated and measured directivities for the hemispherical helices shown in Fig. 5 and Fig. 8.

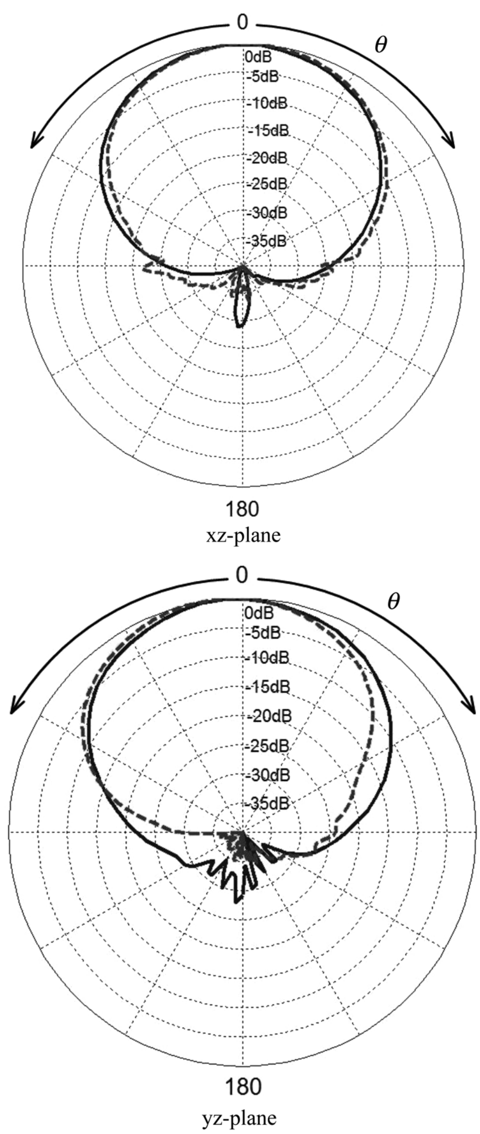

Fig. 12. Simulated and measured normalized radiation patterns for the hemispherical helices of Figs. 5 and 8, simulated (——) and measured (......).

indicates that the proposed antenna is a very efficient and compact UWB radiator. An interesting observation regarding the axial ratio and VSWR is that for both the measured bandwidths are larger than the corresponding predicted ones. In other words, the performance of the constructed prototype antenna is slightly better than expected.

Variations of the simulated maximum directivity and the measured gain versus frequency are illustrated in Fig. 11. As noted, the agreement between the measured and simulated results is very good, with the measured values slightly smaller than predicted ones at most frequencies. This is partly because the conductor loss has been ignored in calculating the directivity results. Far-field patterns of the prototype antenna were also examined for a large number of frequencies. As an example, Fig. 12 illustrates measured and simulated normalized power patterns in the xz- and yz- planes at a frequency of 3.40 GHz. A closer examination of these patterns emphasizes good agreements between measured and simulated results and also ascertains the axial symmetry of the main beam.

V. Conclusion

A new hemispherical helical antenna capable of providing about 9 dB gain and $\mathrm{VSWR} \leq 2$ over a bandwidth of more than 50% and circular polarization $(\text{axial ratio} \leq 3\ \mathrm{dB})$ over a bandwidth of 24% was introduced and investigated. Compared with a wire hemispherical helix, the new design incorporates two major modifications, including the replacement of the wire radiating element with a tapered metallic strip which assumes a non-conformal configuration relative to the hemispherical surface and a matching section consisting of a nonlinearly doubly tapered strip transmission line. A comprehensive numerical analysis of the proposed antenna was carried out. Radiation characteristics including far-field patterns, directivity, axial ratio, VSWR, and beamwidth were calculated over wide frequency ranges. A prototype of the antenna was constructed and measured. Generally, there is good agreement between the simulated and measured radiation characteristics. The low profile, compact geometry, and desirable radiation characteristics over a wide frequency range are important attributes of this antenna which make it an attractive candidate for avionic and UWB communication applications.

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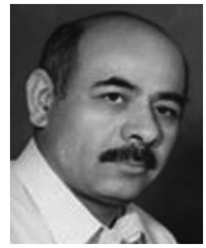

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