MINIATURE HEXAFERRITE AXIAL-MODE HELICAL ANTENNA FOR UNMANNED AERIAL VEHICLE APPLICATIONS

by

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ABSTRACT

Hexaferrite, axial-mode helical antenna is proposed to provide reliable communication for unmanned aerial vehicle (UAV) applications. The conventional axial-mode helical antenna uses an air core or low dielectric material, resulting in large antenna size. To increase the miniaturization factor, \( n = (\mu_\epsilon r)^{0.5} \), a Co\(_2\)Z hexaferrite-glass composite was used as an antenna core. The material properties of ferrite and antenna design were studied to yield the best antenna performance. Axial-mode helical antennas were designed and simulated as well as experimentally fabricated.

The 3-dimensional finite element method (FEM) simulation was performed to design a hexaferrite helical antenna and confirm the axial-mode operation at 2.44 GHz with gain of 2.0 dBi. The designed hexaferrite helical antenna showed 82% volume reduction and good impedance matching compared to the air-core antenna. The axial-mode hexaferrite antenna was fabricated based on the designed structure and characterized in an anechoic chamber. The maximum gain of 0.541 dBi was measured with a pitch angle of 10° at 2.39 GHz.

Finally, a two-element axial-mode antenna array was designed based on the miniature hexaferrite antenna to further improve antenna gain. Maximum gain of 4.5 dBi at 2.43 GHz was simulated for the antenna array. Therefore, high gain and a miniature antenna can be achieved with the combination of Co\(_2\)Z hexaferrite-glass composite and antenna design technology.
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<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Co&lt;sub&gt;2&lt;/sub&gt;Z</td>
<td>Alloy of cobalt and zinc</td>
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<tr>
<td>C</td>
<td>Circumference</td>
</tr>
<tr>
<td>dB</td>
<td>Decibels</td>
</tr>
<tr>
<td>dBi</td>
<td>Decibels Isotropic</td>
</tr>
<tr>
<td>°</td>
<td>Degree</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>(\lambda_{\text{eff}})</td>
<td>Effective Wavelength</td>
</tr>
<tr>
<td>ECE</td>
<td>Electrical and Computer Engineering</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<tr>
<td>GHz</td>
<td>Giga-Hertz</td>
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<tr>
<td>FR4</td>
<td>Glass Epoxy Laminate</td>
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<tr>
<td>HPBW</td>
<td>Half-Power Beamwidth</td>
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<tr>
<td>HFSS</td>
<td>High Frequency Structure Simulator</td>
</tr>
<tr>
<td>hr</td>
<td>Hour</td>
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<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>&lt;</td>
<td>Less Than</td>
</tr>
<tr>
<td>MMDL</td>
<td>Magnetic Materials and Device Laboratory</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>mm</td>
<td>Milli-meter</td>
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<tr>
<td>N</td>
<td>Number of Turns</td>
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\[\Omega\] Ohm

\[O_2\] Oxygen

\[\%\] Percent

\[\mu_r\] Permeability

\[\epsilon_r\] Permittivity

\[\pi\] Pi

\[\alpha\] Pitch Angle

\[Si\] Silicon

\[S\] Spacing

\[UAV\] Unmanned Aerial Vehicle

\[V\] Volt

\[W\] Watt

\[wt\%\] Weight Percent
ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Yang-Ki Hong for his continued support to perform the research of this thesis. I would like to thank my thesis committee including Dr. Jackson, Dr. Burkett, and Dr. Neggers. I would also like to thank my co-workers of the MMDL (Magnetic Materials and Device Laboratory, University of Alabama ECE Department): Jeevan Jalli, Andrew Lyle, Jae-Jin Lee, Jihoon Park, Gavin Abo, Woncheol Lee, Ryan Syslo, and David Gillespie.

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1.0 INTRODUCTION

In section 1.1, the project objectives for my research project are given. In section 1.2, previous work completed is summarized. In section 1.3, the helical antenna is described and defined.

High frequency structure simulation of the axial-mode helical antenna is given in section 2.0. Material fabrication and helical core construction is given in 3.0. The fabrication and characterization of the single element axial-mode helical antenna is described in section 4.0. The design and fabrication of the ferrite antenna array is covered in section 5.0. Outcomes and future work are recited in section 6.0.

Reliable data transmission of high quality video/audio signals is important for unmanned aerial vehicle (UAV) to ground communication. UAVs, especially, are demanded to integrate more functions and decrease in overall size. Accordingly, helical antennas have been introduced in UAVs to meet the aforementioned characteristics (Cravey, 2006).

The helical antennas operate in two principal modes: normal-mode and axial-mode. The normal-mode helical antennas have omnidirectional radiation patterns, while the axial-mode helical antennas have directional radiation patterns and circular polarization (Niow, 2009). Therefore, the axial-mode helical antenna is desired for UAV applications because of its high directivity and circular polarization.

In order to achieve the axial-mode, the circumference, C, of the helical antenna should be in the range of $3/4 \times \frac{C}{\lambda} < C/\lambda < 4/3$ (where $\lambda$ is the wavelength) (Balanis, 2005). As a result, the diameter of the antenna core should be in the range of $29 \text{ mm} \leq D \leq 51.9 \text{ mm}$ at 2.45 GHz.
large size of the antenna core limits the use of axial-mode helical antennas for UAV applications. To reduce antenna size, ferrite has been introduced as an antenna substrate due to possession of both permeability ($\mu_r$) and permittivity ($\varepsilon_r$). The wavelength of incident wave in the ferrite medium can decrease because the wavelength is inversely proportional to $(\mu_r\varepsilon_r)^{0.5}$ (Mosallaei, 2009). In addition, antenna bandwidth and impedance matching can be improved with permeability. Therefore, the application of a ferrite core for axial-mode helical antenna can address the issue of large antenna size.

1.1 Objectives
The objectives of this thesis are to design and fabricate a miniaturized hexa ferrite helical antenna with gain of over 2.0 dBi and develop an array to be implemented in unmanned aerial vehicle applications.

1.2 Previous Work
Communication components for the UAV, including antennas, should be miniaturized to transmit large amounts of data and high quality video images from the UAV to the ground communication centers. Current omnidirectional antennas have low signal-to-noise ratio which leads to low antenna gain. By using a helical antenna and an antenna array, the formed directional radiation pattern can achieve high antenna gain and can increase wireless communication distance. Regarding antenna size, whip antennas in UAV limits the flight time due to high air resistance. The helical antenna can be installed inside the wings of the UAV to save power during long flights and to provide reliable communication.
The physical parameters of the helical antenna have been studied by other researchers to modify properties. The pitch angle and circumference can be varied to change the phase velocity (Kraus, 1988; Mimaki & Nakano, 1998). The ground plane can also be adjusted in shape and size to achieve higher gain and to modify the radiation pattern (Djordjevic et al., 2006).

The core material of the antenna plays a key role in the antenna performance. A hollow dielectric cylinder is generally used for mechanical support for longer antennas. Such materials can influence the resonance frequency and gain. A dielectric material with low loss tangent has been introduced into the helical antenna to reduce the physical size by over 95% (Young, 2011).

An array structure can also be made from multiple single helical antenna elements to increase gain and to adjust the radiation pattern. 1x2 helical arrays are shown to increase HPBW and gain (Ho, 1996) and 2x2 helical arrays also prove to enhance antenna performance for satellite communications (Hui, 2004).

1.3 Definition and Design of Helical Antenna

The helical antenna consists of a helical conductor wrapped around a cylinder with diameter $D$. The distance between each helical turn is described by the spacing, $S$, as shown in Figure 1. The pitch angle, $\alpha$, describes the angle at which the conductor is wrapped around the cylinder. Since the circumference is $C = \pi D$, the pitch angle and spacing are related by the equation $S = C \tan(\alpha)$. The number of helical turns, $N$, can be used to find the total length of the antenna which is $L = NS$. 


Figure 1. The design of the Helical Antenna structure.
2.0 HFSS SIMULATION

A miniature axial-mode helical antenna was designed based on a Co$_2$Z hexaferrite-glass composite core. Performance of the hexaferrite helical antenna was simulated with ANSYS high frequency structure simulator (HFSS version 11) and compared with an air-core axial-mode helical antenna. The geometry and dimensions of the designed hexaferrite helical antenna are shown in Figure 2. The hexaferrite core has a diameter of 16.52 mm and height of 16.8 mm, which is a volume of 3602 mm$^3$. An antenna radiator was designed by helically winding a conductive strip with width of 1 mm, spacing of 4.6 mm and pitch angle of 5.06°. For a grounding plane, a circular plate having a diameter of 100 mm was used. The designed helical antenna was excited by a coaxial feeder. Also, a 2 mm gap between the ground and helical radiator was given to improve impedance matching as shown in Figure 2.
For performance comparison, we have also designed an air-core helical antenna. In order to obtain the axial-mode radiation performance, a diameter and pitch angle of the air-core was 29 mm and 5.06°, respectively. The volume of the air-core helical antenna was 17,960 mm³. The designed air-core antenna had a 100 mm diameter circular ground plane and was fed by a 50 ohm coaxial cable. Regarding material parameters for the hexaferrite core, permeability ($\mu_r$) of 2.02 ($\tan \delta_\mu = 0.08$) and permittivity ($\varepsilon_r$) of 7.44 ($\tan \delta_\varepsilon = 0.005$) were used in the simulation. These values were experimentally obtained from Co$_2$Z hexaferrite (Ba$_3$Co$_2$Fe$_{24}$O$_{41}$)-glass composite and will be discussed in more detail in section 3.

Simulated return loss of the hexaferrite helical antenna is presented in comparison with the air-core antenna in Figure 3 (a). The designed hexaferrite antenna showed a resonance frequency of 2.44 GHz and return loss of 32 dB. On the other hand, the air-core helical antenna
had a resonance frequency of 2.44 GHz and return loss of 11 dB. It was found that the hexaferrite antenna showed much better impedance matching than the air-core antenna, consequently, broader antenna bandwidth. This good impedance matching was attributed to a decrease in the capacitive property due to the small permeability of the Co$_2$Z$_2$-glass composite core. It was also noted that the volume of the hexaferrite antenna was reduced by 82% compared to the air-core antenna.
Figure 3. (a) The simulated return loss, (b) radiation patterns for air-core helical antenna, and (c) radiation patterns for axial-mode hexaferrite helical antenna.
According to equation $\lambda_{\text{eff}} = \frac{\lambda_0}{(\mu_r \varepsilon_r)^{0.5}}$ (where $\lambda_0$ is the wavelength in free space), the wavelength of incident wave in ferrite medium is decreased by $(\mu_r \varepsilon_r)^{0.5}$. The characteristics of broad bandwidth and small form factor for the hexaferrite helical antenna are advantageous to reliable wireless communications for UAV applications. Figure 4(b) shows the simulated radiation pattern of the air-core antenna with gain of 8.8 at 2.44 GHz. The designed hexaferrite antenna has gain of 2.0 dBi at 2.44 GHz and directional radiation patterns along the axis of the helix as shown in Figure 4(c). Therefore, it was confirmed that both antennas operate in the axial-mode.
3.0 MATERIAL FABRICATION

A material desirable for GHz range applications needs to have high permeability, low permittivity, and low loss. According to Figure 4, Co$_2$Z hexaferrite is shown to have appropriate characteristics for the operating frequency of 2.45 GHz. The Co$_2$Z hexaferrite has been previously reported to have permeability of greater than 2.02, permittivity lower than 7, and low loss (Lee, 2011).

Figure 4. Representation of the permeability versus frequency for multiple ferrite materials.
To achieve such characteristics, a modified process was developed to improve the material properties. In order to increase the quality factor ($\mu'/\mu''$) at GHz frequencies, a 40 hr shake-milling process and addition of 2 wt% borosilicate glass was employed. A detailed flow chart is shown in Figure 5.

After the Co$_2$Z barium ferrite was fabricated, borosilicate glass was mixed with the powder after a 40 hr shake milling process to increase density and reduce particle grain size.
Next the powder was formed into a cylindrical core to be used in the helical antenna design. The powder was poured into a pressing die and a mechanical press was used to form the cylinder. Finally, the core was sintered at 950°C for an hour.
4.0 HELICAL ANTENNA FABRICATION AND CHARACTERIZATION

The helical antennas were fabricated and characterized for antenna performance. The designs are based on the simulation results.

4.1 Air Core Helical Antenna

First, the air core was fabricated to confirm the simulated results and secure reliable data before progressing to the hexaferrite helical antenna. To fabricate the air core antenna, a ground plane was formed by cutting a 100 mm diameter circle from a copper sheet. A hole was cut into the copper sheet and a coaxial cable was connected to the bottom to act as the antenna feed. Next, the core was formed by folding a small rectangular piece of transparency paper into a cylindrical shape using tape to hold it together. The transparency paper was used because it has a dielectric constant very close to the dielectric constant of air. After that, the conductor was formed by cutting a 1 mm wide strip out of copper tape and wrapping it around the transparency paper with a spacing of 4.6 mm to match the simulated design. Finally, the wrapped core was secured to the ground plane with double sided tape and the conductor was soldered to the coaxial cable. Figure 6 shows the constructed air core helical antenna.
The antenna was characterized using an anechoic chamber (Raymond EMC QuietBox AVS 700) and a network analyzer (Agilent N5230A) to test for the radiation pattern and resonant frequency. Figure 7 displays the measured resonant frequency and radiation patterns. The antenna results are shown in Figure 7(a) to operate at 2.51 GHz with return loss of 15 dB. The radiation pattern in Figure 7(b) also shows a directional radiation pattern which confirms its operation in the axial mode with gain of 6.8 dBi.
Figure 7. (a) Experimental return loss and (b) radiation patterns for air core design.
4.2 Hexaferrite Helical Antenna

A axial-mode hexaferrite helical antennas with two different core diameters of 14.01 mm and 16.47 mm were fabricated based on the designed structure shown in Figure 2. Photo-image of the fabricated 14.01 mm diameter helical antenna is presented in Figure 8. The Co$_2$Z hexaferrite-glass composite was used as the antenna core. The volume of the ferrite core was 2604 mm$^3$ (diameter = 14.01 mm and height = 16.89 mm) and 3590 mm$^3$ (diameter = 16.47 mm and height = 16.85 mm). A helical radiator was fabricated by wrapping a 1 mm width copper strip (3M copper foil tape 1181) with 3 turns and pitch angle of 5.06°.

![Figure 8. Photograph of the fabricated hexaferrite helical antenna.](image)

A circular copper plate with a 100 mm diameter was used as the ground plane. The fabricated hexaferrite antenna was mounted on top of the ground plane and connected to a 50 ohm coaxial cable. Figure 9(a) shows experimental return loss of the hexaferrite helical antennas in comparison with simulation results. The network analyzer (Agilent N5230A) was used to
measure the return loss. The fabricated antenna with a core diameter of 14.01 mm showed resonance frequency of 2.65 GHz and return loss of 28 dB. The slightly high resonance frequency of the fabricated antenna is due to the smaller diameter of the fabricated core compared to the designed hexaferrite core. It was found that the 16.47 mm hexaferrite core antenna had resonance frequency of 2.44 GHz and return loss of 28 dB, which is in good agreement with the simulated results. Regarding radiation performance, the hexaferrite helical antenna with diameter of 16.47 mm was characterized in the anechoic chamber with the network analyzer.
Figure 9 (b) shows measured radiation patterns with various pitch angles. It was observed that the fabricated hexaferrite antenna had highly directional radiation patterns. Accordingly, the miniature hexaferrite helical antenna is applicable to mobile communication applications. It was also found that the total gain of the axial-mode hexaferrite antenna increased by increasing the alpha from 4° to 10°. The maximum gain of 0.541 dBi was measured with the pitch angle of 10° at 2.39 GHz. It was found that the measured gains were lower than the simulated gain of 2.0 dBi. This is mainly attributed to high magnetic loss of the Co$_2$Z-glass composite core. The further increase in antenna gain is achievable by decreasing magnetic loss.
tangent (Young, 2011). It is suggested that both permeability and permittivity of Co$_2$Z hexaferrite-glass composite was effective in the development of miniature axial-mode helical antenna.

4.3 Microstrip Hexaferrite Helical Antenna

To prepare for a multi-element helical antenna array, a microstrip hexaferrite helical antenna was designed. The feed line was modified to later accommodate a power dividing circuit for multiple antenna elements. A double-sided copper clad laminate FR4 substrate was used as the ground plane. A milling machine was used to etch the copper to make the 50 ohm matching feed line. The fabricated antenna can be seen in Figure 10.

![Figure 10. Photograph of the fabricated microstrip hexaferrite helical antenna.](image)
The antenna showed a resonant frequency of 2.55 GHz with a return loss of 21 dB. The radiation pattern was very similar to the previous antennas which displayed directional radiation patterns proving axial-mode operation. The maximum gain was recorded at 0.227 dBi.
5.0 HELICAL ANTENNA ARRAY

To further improve the directivity and gain of the antenna, we have also designed a two-element axial-mode antenna array based on the microstrip miniature hexaferrite antenna. The feed line was designed into a power dividing circuit that equally split the power to each of the antenna elements. The feed line was made for 50 ohm matching.

A coplanar microstrip line was used as the feeding structure. A double-sided copper clad laminate FR4 substrate was used as the ground plane. The designed antenna can be seen in Figure 11.

![Figure 11. The design of the hexaferrite antenna array.](image-url)
The simulation results show an improvement in antenna gain. The return loss can be seen in Figure 12(a) and shows the antenna operating at 2.43 GHz with a return loss of 16 dB. The radiation pattern is shown in Figure 12(b) and has a maximum gain of 4.5 dBi.
After achieving acceptable simulation results, the array was fabricated based on the simulated design. The double-sided copper clad laminate FR4 substrate was again used for the ground plane. The new feed was designed in software and a milling machine was used to cut out the board and etch the copper from the selected areas. Next, the coaxial cable was connected to the ground plane and the copper conductor was carefully wrapped around the ferrite core to match the spacing and pitch angle of the simulated design. The final fabricated antenna is shown in Figure 13.

Figure 12. (a) The simulated return loss and (b) radiation patterns for hexaferrite helical antenna array.
Figure 13. (a) Photograph of the fabricated hexaferrite helical array antenna and (b) experimental radiation patterns.
The experimental results showed a gain of -1.1 dBi at 2.56 GHz. This is significantly lower than simulation data due to the reduced turn spacing of the antenna elements. The pressing process was very difficult and did not achieve two cores of at least 16.8 mm in height. The pressing die wore out after a few uses causing excessive vibration when extracting pressed core. Most attempts resulted in broken or cracked samples which were ground back into powder and repressed. The next tallest sample was 13.5 mm which reduced the turn spacing for both elements. This caused interference between turns which brought the total gain of the antenna down.
6.0 CONCLUSIONS

A miniature axial-mode helical antenna was designed and fabricated based on a Co$_2$Z$_2$ hexaferrite-glass composite core having permeability of 2.02, tan $\delta_\mu$ of 0.08, permittivity of 7.44, and tan $\delta_\varepsilon$ of 0.005. The designed hexaferrite helical antenna showed size reduction of 82% as compared to the air-core axial-mode antenna. Measured return loss of the fabricated hexaferrite antenna was 28 dB at 2.44 GHz. Also, the experimental radiation patterns confirmed axial-mode operation with gain of 0.54 dBi. The measured gain was found to be lower than simulated gain of 2.0 dBi due to relatively high magnetic loss tangent of Co$_2$Z$_2$-glass composite.

Further antenna simulations showed that a two-element hexaferrite helical array considerably increased gain to 4.5 dBi. It was demonstrated that addition of Co$_2$Z$_2$ hexaferrite-glass composite having both permeability and permittivity played a key role in the miniaturization of axial-mode helical antenna.

6.1 Future Work

Future work will be to develop an improved method for pressing cylindrical ferrite cores. Once this process is mastered, a 9 element array helical antenna with phase shifters can be developed to increase the antenna gain and directionality as seen in Figure 14.
Figure 14. The helical antenna array with 9 elements and phase shifters.
REFERENCES


Miniature Hexaferrite Axial-Mode Helical Antenna for Unmanned Aerial Vehicle Applications

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We demonstrated the size reduction of axial-mode helical antenna based on Co$_3$Z hexaferrite-glass composite. Axial-mode helical antenna was employed to provide reliable communication for unmanned aerial vehicle (UAV) applications. The conventional axial-mode helical antenna uses an air core or low dielectric material, resulting in large antenna size. To increase the miniaturization factor $n = (\mu_r/\varepsilon_r)^{1/2}$, a Co$_3$Z hexaferrite-glass composite was used as an antenna core. The 3-dimensional finite element method (FEM) simulation was performed to design a hexaferrite helical antenna and confirm the axial-mode operation at 2.44 GHz with gain of 2.0 dBi. The designed hexaferrite helical antenna showed 82% of volume reduction and good impedance matching compared to the aircore antenna. The axial-mode hexaferrite antenna was fabricated based on the designed structure and characterized in an anechoic chamber. The maximum gain of 0.541 dBi was measured with the pitch angle of 10° at 2.39 GHz. Also, a two-element axial-mode antenna array was designed based on the miniature hexaferrite antenna to further improve antenna gain. Maximum gain of 4.5 dBi at 2.43 GHz was simulated for the antenna array. Therefore, high gain and miniature antenna can be achieved with the combination of Co$_3$Z hexaferrite-glass composite and antenna design technology.

Index Terms—Helical antenna, Axial-mode, Hexaferrite, Unmanned Aerial Vehicle

I. INTRODUCTION

Reliable data transmission of high quality video/audio signals is important for unmanned aerial vehicle (UAV) to ground communication. UAVs, especially, are demanded to integrate more functions and decrease in overall size. Accordingly, helical antennas have been introduced in UAVs to meet the aforementioned characteristics [1]. The helical antennas operate in two principal modes: normal-mode and axial-mode. The normal-mode helical antennas have omnidirectional radiation patterns, while the axial-mode helical antennas have directional radiation patterns and circular polarization [2]. Therefore, the axial-mode helical antenna is desired for UAV applications because of its high directivity and circular polarization. In order to achieve the axial-mode, the circumference (C) of the helical antenna should be in the range of $3/4 < C/\lambda < 4/3$ (where $\lambda$ is the wavelength) [3]. As a result, diameter ($D = C/\pi$) of the antenna core should be in the range of $29$ mm $\leq D \leq 51.9$ mm at 2.45 GHz. The large size of antenna core limits the use of axial-mode helical antennas for UAV applications.

To reduce antenna size, ferrite has been introduced as an antenna substrate due to possession of both permeability ($\mu_r$) and permittivity ($\varepsilon_r$). The wavelength of incident wave in the ferrite medium can decrease because the wavelength is inversely proportional to $(\mu_r/\varepsilon_r)^{0.5}$ [4]. In addition, antenna bandwidth and impedance matching can be improved with permeability [5]. Therefore, the application of a ferrite core for axial-mode helical antenna can address the issue of large antenna size.

In this paper, we report a miniature axial-mode helical antenna based on Co$_3$Z hexaferrite-glass composite. Measured and simulated performances of the axial-mode hexaferrite antennas are also reported.

Digital Object Identifier inserted by IEEE

II. SIMULATION OF AXIAL-MODE HEXAFERRITE HELICAL ANTENNA

A miniature axial-mode helical antenna was designed based on Co$_3$Z hexaferrite-glass composite core. Performance of the hexaferrite helical antenna was simulated with ANSYS high frequency structure simulator (HFSS ver. 11) and compared with an air-core axial-mode helical antenna. The geometry and dimensions of the designed hexaferrite helical antenna are shown in Fig. 1. The hexaferrite core has a diameter of 16.52 mm and height of 16.8 mm, which is a volume of 3601 mm$^3$. An antenna radiator was designed by helically winding a conductive strip with width of 1 mm, spacing of 4.6 mm and pitch angle of 5.06°. For the grounding plane, a circular plate with a diameter of 100 mm was used. The designed helical antenna was excited by a coaxial feeder. Also, a 2 mm gap between the ground and helical radiator was given to improve impedance matching as shown in Fig. 1.

FIG. 1 HERE

For performance comparison, an air-core helical antenna was designed with the same height of 16.8 mm and spacing of 4.6 mm as the hexaferrite core antenna. In order to resonate at 2.45 GHz, the diameter of air-core increased to 29 mm from 16.52 mm. The volume of the designed air-core helical antenna was 17,960 mm$^3$ (diameter of 29 mm and height of 16.8 mm). The air-core antenna has a 100 mm diameter circular ground plane and was fed by a 50 ohm coaxial cable.

Regarding material parameters for the hexaferrite core, permeability ($\mu_r$) of 2.02 (tan $\delta_r = 0.08$) and permittivity ($\varepsilon_r$) of 7.44 (tan $\delta_r = 0.005$) were used in the simulation. These values were experimentally obtained from Co$_3$Z hexaferrite
(Ba$_3$Co$_{2}$Fe$_{25}$O$_{41}$)-glass composite. A Co$_2$Z-glass composite core was prepared by pressing a mixture of 40 hr shake-milled Co$_2$Z hexaferrite and 2 wt% borosilicate glass in a cylindrical mold. A green body was sintered at 950 °C for 2 hr in an oxygen environment. A detailed process for the Co$_2$Z-glass composite was reported elsewhere [6]. The Co$_2$Z-glass composite showed much higher quality factor ($Q''/Q'$) at GHz frequencies due to an increase in magnetic anisotropy field (i.e. FMR frequency) and small grain size [6] than Co$_2$Z hexaferrite [7]. This relatively high quality factor characteristic of the Co$_2$Z-glass composite was demonstrated by GPS and Bluetooth GHz antenna performances [8, 9].

**FIG. 2 HERE**

Simulated return loss of the hexaferrite helical antenna is presented in comparison with the air-core antenna in Fig. 2 (a). The designed hexaferrite antenna showed a resonance frequency of 2.44 GHz and return loss of 32 dB. On the other hand, the air-core helical antenna had a resonance frequency of 2.44 GHz and return loss of 11 dB. The fractional bandwidth at VSWR = 3:1 was obtained to be 4.3 % for the air-core antenna and 8.6 % for the hexaferrite antenna. The hexaferrite antenna showed better impedance matching than the air-core antenna. This is attributed to permeability ($\mu_r = 2.02$) and magnetic loss tangent (tan $\delta_p = 0.08$) of the Co$_2$Z-glass composite. The quality factor of the antenna decreased with magnetic loss tangent, thereby increasing return loss i.e. impedance matching. Further, narrow bandwidth of the helical antennas can be increased with large axial length and great number of turns [10]. It was noted that the volume of the hexaferrite antenna was reduced by 82 % compared to the air-core antenna. According to $\lambda_{eff} = \lambda_0/(\mu_r\tan\delta_p)^{0.5}$ (where $\lambda_0$ is the wavelength in free space), wavelength of incident wave in ferrite medium is decreased by $(\mu_r\tan\delta_p)^{0.5}$. The characteristics of broad bandwidth and small form factor for the hexaferrite helical antenna are advantageous to reliable wireless communications for UAV applications. The simulated radiation patterns of the air-core and hexaferrite antennas are presented in Fig. 2 (b). The maximum gain of hexaferrite and air-core antennas was 2.0 dB and 8.8 dB at 2.44 GHz, respectively. Low gain of the hexaferrite antenna is attributed to relatively high magnetic loss tangent (tan $\delta_p$), short axial length and small $C/\lambda$ ratio ($C/\lambda = 0.42$). The gain of axial-mode helical antenna is affected by the pitch angle and axial length of the helix [11]. Also, the decrease in $C/\lambda$ ratio led to the significant decrease in antenna gain [12]. It was found that both hexaferrite and air-core antennas showed directional radiation patterns along the axis of the helix. This confirms that the antennas operate in the axial-mode.

**FIG. 3 HERE**

III. FABRICATION AND MEASUREMENT RESULTS

The axial-mode hexaferrite helical antennas with two different core diameters of 14.01 mm and 16.47 mm were fabricated based on the designed structure shown in Fig. 1. Photo-image of the fabricated 14.01 mm diameter helical antenna is presented in Fig. 3. The Co$_2$Z hexaferrite-glass composite was used as the antenna core. The volume of the ferrite core was 2604 mm$^3$ (diameter = 14.01 mm and height = 16.89 mm) and 3590 mm$^3$ (diameter = 16.47 mm and height = 16.85 mm). A helical radiator was fabricated by wrapping a 1 mm width copper strip (3M copper foil tape 1181) with 3 turns and pitch angle of 5.06°. A circular copper plate with a 100 mm diameter was used as the ground plane. The fabricated hexaferrite antenna was mounted on top of the ground plane and connected to a 50 ohm coaxial cable.

**FIG. 4 HERE**

Fig. 4 (a) shows experimental return loss of the hexaferrite helical antennas in comparison with simulated result. A network analyzer (Agilent N5230A) was used to measure the return loss. The fabricated antenna with a core diameter of 14.01 mm showed resonance frequency of 2.65 GHz and return loss of 28 dB. The slightly high resonance frequency of the fabricated antenna is due to the smaller diameter of the fabricated core than the designed hexaferrite core. It was found that the 16.47 mm hexaferrite core antenna had resonance frequency of 2.44 GHz and return loss of 28 dB, which is in good agreement with the simulated result. Regarding radiation performance, the hexaferrite helical antenna with diameter of 16.47 mm was characterized in an anechoic chamber (Raymond EMC QuietBox AVS 700) with the network analyzer (Agilent N5230A). Fig. 4 (b) shows measured radiation patterns with various pitch angles. It was observed that the fabricated hexaferrite antenna had directional radiation patterns. Accordingly, the miniature hexaferrite helical antenna is applicable to UAV applications. It was also found that the total gain of the axial-mode hexaferrite antenna increased by increasing the pitch angle from 4° to 10°. The maximum gain of 0.541 dBi was measured with the pitch angle of 10° at 2.39 GHz. It was found that the measured gains were lower than the simulated gain of 2.0 dBi. This is mainly attributed to high magnetic loss of the Co$_2$Z-glass composite core. The increase in antenna gain is achievable by decreasing magnetic loss tangent of the hexaferrite [13]. Accordingly, the low-loss GHz hexaferrite is under development. We will compare the size reduction and performance of low-loss hexaferrite helical antenna with high permittivity dielectric antenna. In the next section, we will discuss the antenna performance improvement by an array of helical antenna elements.

**FIG. 5 HERE**

IV. TWO-ELEMENT HEXAFERRITE HELICAL ARRAY

A two-element antenna array was designed based on the miniature hexaferrite antenna element to further improve the directivity and gain of the antenna as shown in Fig. 5. A
coplanar microstrip line was used as a feeding structure. The power dividing circuit was designed to equally split the power and give 50 ohm impedance matching. A double-sided copper clad laminate FR4 substrate was used as the ground plane. The distance between the two elements was 58 mm. The designed antenna array had a return loss of 16 dB at 2.43 GHz. Maximum gain of 4.5 dBi was simulated at 2.43 GHz as shown in Fig. 5 (b). It is noted that the miniaturization of single hexaferrite antenna element in the antenna array allows effective space utilization in the limited space of UAV platform compared to the conventional helical antenna [14, 15]. The hexaferrite array antenna can achieve beam steering with phase shifters and further improvement of the antenna directivity.

Our simulation and experimental results showed that Co-Z glass composite had a large contribution to antenna size reduction and impedance matching. Also, it was demonstrated that high gain and miniature mobile antennas can be realized with the combination of antenna design and hexaferrite technologies.

V. CONCLUSION

A miniature axial-mode helical antenna was designed and fabricated based on a Co-Z hexaferrite-glass composite core having permeability of 2.02, tan δh of 0.08, permittivity of 7.44, and tan δe of 0.005. The designed hexaferrite helical antenna showed size reduction of 82% as compared to the air-core axial-mode antenna. Measured return loss of the fabricated hexaferrite antenna was 28 dB at 2.65 GHz. Also, the experimental radiation patterns confirmed axial-mode operation with gain of 0.54 dBi at 2.45 GHz. The measured gain was found to be lower than the simulated gain of 2.0 dBi due to relatively high magnetic loss tangent of Co-Z-glass composite. Further antenna simulation showed that the two-element hexaferrite helical array considerably increased gain to 4.5 dBi. It was demonstrated that addition of Co-Z hexaferrite-glass composite having both permeability and permittivity plays a key role in the miniaturization of axial-mode helical antenna.

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Fig. 1. Geometry and dimensions of simulated hexaferrite helical antenna.

Fig. 3. Photo-image of fabricated hexaferrite helical antenna.

Fig. 2. (a) Simulated return losses and (b) radiation patterns for the air-core and hexaferrite helical antennas.

Fig. 4. (a) Measured and simulated return loss and (b) radiation patterns for fabricated hexaferrite helical antennas with diameter of 16.47 mm.
Fig. 5. (a) Design of two-element helical antenna array and (b) simulated radiation patterns at 2.43 GHz.