Room temperature densified ceramics for weight optimized circular polarized GPS antenna design

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1 Introduction

Devices with navigation properties that use satellite systems are becoming ubiquitous and these devices demand high performance within a limited volume. With the advent of Internet of Things (IoT), many devices also need to have positional information. The IoT connectivity is done through cellular network and accurate positional information requires the use of satellite systems in combination with the cellular networks. Owing to the new demand of different form factors required for these devices, there is an urgent need to create fabrication methodologies and antenna structures which are easy to customize according to the needs of the specific end product. Ceramic antennas have been widely used to create antenna structures for devices requiring accurate positioning, such as navigation devices. However, typical ceramics substrates are typically manufactured at high temperatures of 850–1300°C which requires special molds and kilns to create the structure. Moreover, the process needs to be accurately controlled to avoid unwanted diffusion, obtain correct phases and predefined sintering shrinkages, and minimize unwanted deformations.

In our study, microwave dielectric lithium molybdate (Li₂MoO₄) was selected as a substrate ceramic due to the easy fabrication of Li₂MoO₄ ceramic components and feasible dielectric properties. Li₂MoO₄ ceramics can be fabricated with a room temperature densification method based on a small amount of aqueous Li₂MoO₄ and its subsequent recrystallization. Densification of the ceramic occurs at the ambient temperature during compact pressing and is followed by a postprocessing step at 120°C to remove residual water from the compact. These Li₂MoO₄ ceramics exhibit relative permittivity (εr) of 5.1 and a dielectric loss value (tan δ) of 0.00035 at 9.6 GHz.¹ It has been shown earlier that Li₂MoO₄ is feasible as a low-loss substrate for antennas.² The dielectric properties of Li₂MoO₄ ceramics can be adjusted with the addition of other oxide materials, such as TiO₂ and BaTiO₃.³,⁴

Antennas for the devices using the satellite systems benefit from having circular polarized antennas, as they have the best polarization match to the satellites.⁵ For a GPS system, the antenna needs to have right-hand circular polarization (RHCP).⁶ There are several ways of creating circular polarisation, as reported. Some of the reported structures are single feed circular patch antenna,⁷ single feed square patch antenna with corner truncation,⁸ dual feed square patch antenna,⁸ stacked patch antenna,⁹ and so on. Conformal

Abstract

This article presents the use of ceramic composite composed of Li₂MoO₄ and 9 vol% of BaTiO₃ to realize compact weight optimized circular polarized GPS antenna. The ceramic substrate for the antenna was fabricated with a room-temperature densification method based on the use of a small amount of an aqueous phase of Li₂MoO₄ and subsequent recrystallization. A square patch (FT-FB) was used as a reference patch antenna. This was then compared with a double curved patch antenna (CT-CB) and a curved patch with a flat bottom (CT-FB). It was observed that the axial ratio and radiation patterns of the different patch antennas were very similar. In simulations, the FT-FB patch had peak total efficiency of −2.2 dB, followed by the CT-CB patch with total efficiency of −2.5 dB and the CT-FB patch with total efficiency of −2.7 dB. The mass of the FT-FB and CT-CB antennas were 12.66 g, while the mass of the CT-FB antenna was only 9.44 g. Thus, a weight reduction of 25.4% was obtained. Ease of fabrication using Li₂MoO₄-based composite ceramic helps in creating an optimal antenna design for size and weight-constrained mobile devices such as drones.
patch antenna designs have also been studied earlier. A square patch on a cylindrical surface\textsuperscript{10-12} and on a sphere\textsuperscript{13-15} has been studied, showing the feasibility of such designs. A crucial aspect of antennas, other than their performance level, is also their size and weight. To minimize the size of the patch element, a substrate material with high permittivity, like ceramic, is often used. This, however, has an implication on the weight of the antenna; the ceramic adds additional material, increasing the total mass of the structure, which is not desirable.

In this study, the following single feed corner truncated square patch antennas were studied

1. with flat top and bottom surfaces (FT-FB),
2. on a truncated spherical substrate, that is, a curved top and bottom (CT-CB), and
3. top surface on a truncated spherical substrate with flat bottom, that is, a curved top and a flat bottom (CT-FB).

2 Antenna structure and design

The initial dimensions for the square patch antenna (FT-FB) were obtained from the following equations\textsuperscript{16}:

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} \left( \frac{1}{\sqrt{1+12h/L}} \right)
\]

\[
\Delta L = 0.412h \left( \frac{\varepsilon_{\text{eff}}+0.3}{\varepsilon_{\text{eff}}-0.258} \right) \left( \frac{w}{h} + 0.813 \right)
\]

\[
L = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L
\]

where, \( f_0 \) is the resonant frequency (Hz), \( \varepsilon_r \) is the dielectric constant, \( c \) is the speed of light in vacuum (m/s), \( h \) is the height, \( w \) is the width, and \( L \) is the length of the substrate (mm).

The patch was designed to be slightly bigger than the design values to take into account the difference between simulation and fabrication. Also, the single feed patch is to operate in circular polarization, which means it must be able to excite two modes whose arithmetic mean is the desired frequency of operation. The corners of the designed patch were then truncated to form a perturbation, creating two orthogonal modes, TM01 and TM10, of the same amplitude and quadrature phase. These two modes add up to create the circular polarization. Depending on the location of the feed and the truncation corner, the antenna can be made to be either right-hand circular polarized (RHCP) or left-hand circular polarized (LHCP). The truncation is typically done at
two corners, and in such a case the feed is placed at the middle of the edge as suggested in ref. [8]. However a quadrature phase shift to the second mode can also be achieved by utilizing truncation only at one corner of the patch which requires the feed location to be slightly off-centered. The position was optimized by modelling the antenna in a FIT solver CST Microwave Studio.\(^{17}\)

Sketch of the patch antenna is shown in Figure 1 along with its dimensions. The FT-FB antenna, Figure 1A, has dimensions of 31.4 mm \(\times\) 31.4 mm \(\times\) 4 mm and a mass of 12.66 g. The area of the patch is 29 mm \(\times\) 29 mm. A triangular truncation of 4.7 mm \(\times\) 4.7 mm was made in one corner of the square patch. This patch was fed with a probe feed with a diameter of 0.35 mm. Similarly the CT-CB antenna, Figure 1B, has dimensions of 31.4 mm \(\times\) 31.4 mm \(\times\) 4 mm, with a mass of 12.66 g, but both the top and bottom surfaces are curved as a truncation for a sphere with a radius of 71.3 mm. Owing to the curvature, the length of the arc of the substrate patch was 31.6 mm in both directions. A patch with dimensions of 29.2 mm \(\times\) 29.2 mm was designed to obtain a good compromise between the axial ratio (<3dB) and \(S_{11}\) (<−10 dB) at the frequency of operation, 1575 MHz. For the third version of patch, CT-FB (Figure 1C), the bottom surface is flat and the top surface is curved, as a truncation of a sphere with a radius of 71.5 mm. The dimensions of the top profile were 29.4 mm \(\times\) 29.4 mm with a mass of 9.44 g. The resultant arc length of the top curved surface's edges is 29.65 mm. Due to the proximity of the corners to the ground at the edges of the patch, there is a loading effect that shifts the resonant frequency lower, as also observed in ref. [13]. Hence, the CT-FB patch antenna dimensions required to excite the resonance at 1575 MHz is smaller than in the previous two cases. Thus lower amount of composite material is enough to fabricate the CT-FB antenna compared to FT-FB and CT-CB antennas which results in the CT-FB sample to have lower mass.

### 3 Experimental procedure

The initial powder particle size of the Li$_2$MoO$_4$ (99+%; Alfa Aesar, Karlsruhe, Germany) was reduced by milling in ethanol with a ZrO$_2$ milling medium and sieving with a mesh size of 180 μm. Commercial BaTiO$_3$ nanopowder (99.9%, 200 nm, tetragonal, US Research Nanomaterials, Inc.) corresponding to 9 vol% of Li$_2$MoO$_4$ powder was ultrasonicated in ethanol to remove possible agglomerates. The resulting slurry was mixed with Li$_2$MoO$_4$ in ethanol with ZrO$_2$ as a milling medium (40 min, 100 rpm) and dried in an oven at 90°C. The composite powder was then sieved with a mesh size of 180 μm. The powder was moistened and pressed uniaxially into a steel mold under pressure of 150 MPa to produce a disk with a diameter of 20 mm. The disk was dried at 120°C for 24 h and then thinned and polished with P1200 carborundum paper (EcoWet, KWH Mirka Ltd, Jepua, Finland) using ethanol. Microstructure imaging of the disk sample was done with a field-emission scanning electron microscope (FESEM; Zeiss Sigma, Carl Zeiss, Germany). The crystal structure of the samples was studied by X-ray diffraction (XRD) using CuK$_\alpha$ radiation (Bruker D8 Discover X-Ray Diffractometer, Karlsruhe, Germany). Silver electrodes were sputtered on both sides of the disk.

After verifying the properties of the material, three composite patches were pressed from moistened powder uniaxially into a brass mold under pressure of 140 MPa for a period of 10 min and dried at 120°C for 24 h. The basic fabrication method is the same as described earlier in refs. [1,2] in more detail. Silver paste was printed on the substrate, one side at a time, using a FluidAmat© process and cured using a conventional oven with a temperature profile of 105–115°C for a duration of 25 min. Each patch was directly fed from the bottom using a coaxial cable. The center conductor of the coax is connected to the top patch and the shield is connected to the bottom ground layer. Images of the fabricated patch antennas are presented in Figure 2. Reflection loss (S$_{11}$) measurements were conducted with a network analyzer (Rohde & Schwarz, ZVB20) and total efficiency was measured in an SATIMO Stargate 64 anechoic chamber. The measurements were done at ambient room temperature and ambient humidity level.

### 4 Results and discussion

Figure 3A,B shows the X-ray diffraction pattern and the backscattered electron images of the sample, respectively.
The diffraction pattern shown only the peaks arising from the addition of BaTiO₃ compared to Li₂MoO₄ powder indicating that there is no reaction between the materials. This is in accordance to the earlier reported results in ref. [3].

In Figure 3B, the light colored bumpy particles belong BaTiO₃ phase. A εᵣ of 10.5 and a tan δ value of 0.006 at 1 GHz were measured with an RF impedance/material analyzer (E4991A; Keysight Technologies, Santa Rosa, CA). Improvements of grinding and pressing process results in better permittivity values than reported in the earlier publication.³

Figure 4 shows the simulated and measured results of the three patch antennas. Figure 4A shows the return loss (S₁₁), while Figure 4B shows the total efficiencies. Figure 5A shows the axial ratio of the YZ plane and Figure 5B shows the graph of axial ratio versus frequency. As explained in Section 2, the final dimensions of the patch were obtained by iterative tuning in CST Microwave Studio. To do this, a design goal of S₁₁ < −10 dB was used, which means 90% of the input power goes into the antenna.

Simulation and measurement results demonstrate that S₁₁ is about −10 dB or better at the desired operating frequency range of GPS.

The simulated efficiency of the FT-FB, CT-CB, and CT-FB antennas were −2.2, −2.5, and −2.7 dB, respectively. This shows that the efficiency of the patch antenna with a flat bottom ground and curved top is about 0.5 dB lower than that of the reference fully flat patch antenna. The measured total efficiencies of the FT-FB, CT-CB, and CT-FB antennas were −3.6, −3.6, and −4.1 dB, respectively, at 1575 MHz. A difference in resonant frequency and efficiency between the simulations and the prototype was observed. This is due to tolerances in the fabrication process of the materials and the patch antennas. The length and width of the patch were according to the mold dimensions. Some variation in curvature was observed due to the uniaxial press, as discussed in Section 3. Other causes for difference in performance can be attributed to the conductivity of the silver ink and to the surface roughness, which cause a drop in efficiency due to higher resistive losses.
The main figure of merit for circular polarized antennas compared with linear polarized antennas is the axial ratio. Typically, a value below 3 dB is considered a threshold design target at the operating frequency. From Figure 5A, it can be observed that the axial ratio in the YZ planes of all three patch antennas show similar circular polarization properties with almost pure LHCP radiation toward the boresight. The 3 dB axial ratio bandwidth toward the boresight for the three antennas is between 102° and 108°. Figure 5 shows the LHCP and RHCP gain of the three simulated patch antennas, in YZ plane, which clearly shows that the desired polarization pointing towards the sky.

The results measured from the prototype show some variation in the axial ratio pattern compared with the simulations. The substrate needs to have a uniform profile along the radiator patch. Due to the uniaxial press method, it is expected that the compressive force is not uniform across the surface area of the antennas causing nonuniformity across the surface area. Hence the summation of two orthogonal modes is not ideal. The axial ratio bandwidth with respect to frequency towards the boresight shows consistent results. The 3 dB axial ratio bandwidth in simulation was 15, 12, and 15 MHz, whereas the measured prototypes showed slightly wider bandwidth of 20, 12, and 20 MHz for FT-FB, CT-CB, and CT-FB antennas, respectively. It is well known that the axial ratio bandwidth of a patch antenna will be better if the ground plane is large. The ground plane is exactly the same size as the patch antenna. Hence the bandwidth values are narrower than typically reported in the literature. Figure 6 shows the LHCP and RHCP radiation pattern of simulations of the FT-FB, CT-CB, and CT-FB antennas.

5. Conclusion

This study demonstrates that composite Li$_2$MoO$_4$ ceramics fabricated by the room temperature densification method can be used to create conformal antenna designs, thus leading to easier and cost-effective customization for a specific conformal space of the end product. The densification process needs to be well controlled to have homogenous substrate parameters. The designed patch antenna, CT-FB, with spherical top surface and flat bottom surface can be used as conformal antenna for applications such as small drones with minimal drop in performance (0.5 dB in this study) compared to square patch, FT-FB. This gives the best volume utilization in conformal space. Also the flat bottom surface (ground) makes mounting easier on circuit board or directing mounting of lumped components below the antenna. The CT-FB antenna gives about 25% weight reduction of the ceramic block compared to FT-FB antenna. This leads to lighter antenna module, a critical design factor for battery driven mobile devices, for example, drones.
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