Laser fabrication of GPS conformal antennas

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ABSTRACT

The Global Positioning System (GPS) has become a mature technology and is continually being applied in new and more demanding applications. A current effort in this area is the development of compact, durable but lightweight GPS antennas on conformal surfaces for handheld devices. Because modeling the electromagnetic performance of these antennas is often difficult, prototypes are typically built, measured and redesigned in an iterative process. We demonstrate the fabrication of a GPS conformal antenna under ambient-temperature conditions using a combination of laser micromachining and/or laser direct-write processes. The electromagnetic behavior of the antennas is then characterized and the design of the antenna structures is further optimized. Pattern simulations and input impedance measurements of the antenna are presented that demonstrate the usefulness and success of the iterative process made possible with this fabrication technique .

Keywords: Conformal antennas, laser micromachining, laser direct-write, laser microfabrication, rapid prototyping, GPS.

1. INTRODUCTION

There is an increasing requirement for conformal antennas to be integrated into mobile communication, sensing network, and air- and space-borne systems. Their covertness, ease of circuit integration, increased reliability and potentially improved performance are factors that are driving their current development. Some drawbacks that have hindered the widespread adoption of conformal antenna systems in the past are the difficulty of design and manufacture with the resultant cost and time expense. While various conformal antenna designs have been modeled and constructed on simple three-dimensional surfaces such as cylinders[1], more complex 3-D shapes remain a challenge. Although the software for designing conformal antennas has increased in sophistication, care must still be taken to interpret and apply the results correctly. Typically, the antenna design on its supporting structure is fabricated several times to validate the predictions and results of the models. This helps to improve the quality of and confidence in the model, and ultimately shortens the time from initial design to completed device.

Recently, we have used rapid prototyping based on laser-machining and laser direct-write to successfully fabricate a variety of electronic and microwave components[2,3]. These components, including resistors[4], capacitors[5] and bandpass filters[6,7] were assembled on planar substrates and exhibited good performance at microwave frequencies. There was relatively good agreement between design and final properties of these components as well. One strength of this technique is that it not only allows for quick comparison between experiment and theory but also enables design changes to be quickly implemented midway during the manufacturing process in order to accommodate materials and processing variations. This rapid prototyping technique has now been used to laser-machine a conformal antenna design on the exterior surface of a dome-shaped structure that is integrated onto a larger package. This spherically-shaped structure was the only place available on the package for an antenna due to limitations in geometry and space.

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In its final form, it will function as both an antenna operating at GPS frequencies in almost any orientation as well as a rugged cover for support electronics.

2. TECHNICAL APPROACH

The laser prototyping system[2] used previously for flat samples was modified for rotary motion as shown in Fig. 1. Baseplates for flat and spherical samples were mounted with self-locating magnetic stops to allow quick interchange between the two geometries.

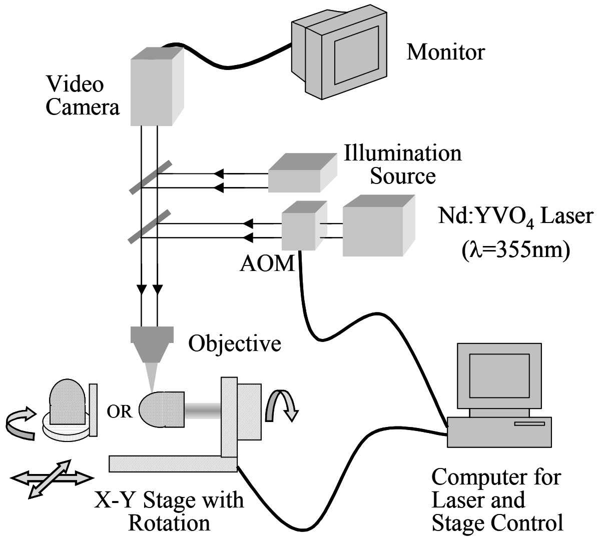

Fig. 1. Diagram of the laser micromachining system adapted for rotating spherically symmetric objects. The dome structure can be rotated in two different orientations. The rotary stage directly underneath the dome is manually operated.

The laser pulses from a high-rep-rate tripled Nd:YVO$_4$ laser operating at 355 nm are focused through an objective onto the workpiece. The 30 ns FWHM pulses are controlled in amplitude and time through an acousto-optic modulator (AOM). The laser focal spot is typically 10 μm in diameter or 40 μm square and the energy per pulse is adjusted to yield fluences of over 2 J/cm^2 on the sample. The workpiece can be mounted in two different orientations on a rotary stage which itself is mounted on top of an X-Y translation stage pair. Motion of all the stages as well as the laser pulses (through the AOM) is controlled and synchronized through a computer. In-line viewing of the sample is accomplished through a CCD camera and monitor providing a total system magnification of over 600X. A photograph of the actual sample mounted on the various stages is shown in Fig. 2.

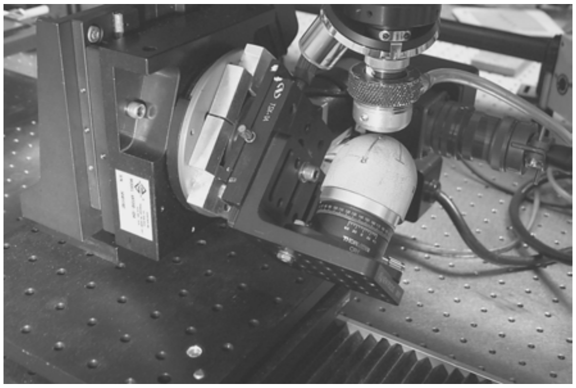

Fig. 2. Photograph of the metal-coated (DuPont CB230) fiberglass dome mounted in the rotary stage.

Various polymer compounds and composites such as polypropylene, Ultem, PVDF, and fiberglass were explored as possible candidates for the support structure of the antenna. The candidate material should have a high dielectric constant (at microwave frequencies), an operating temperature sufficiently high for materials processing, low material and manufacturing costs, good mechanical strength and a reasonable laser ablation threshold. Based on these requirements, fiberglass was chosen as the material for the first prototype. Each fiberglass dome was manufactured with a 6-ply layering process to yield a dome ~ 50 mm diameter x 43 mm high x 1.7 mm thick. Each dome was then heat-treated to raise its heat deflection temperature to ~ 200 °C.

Various metal inks and processing parameters for their application to the fiberglass dome were also surveyed. The metal layer was required to be solderable, possess good conductivity, be easily laser-machined, processes below the softening temperature of the substrate, and have good adhesion with the surface. A commercial Ag-coated Cu paste (DuPont CB230) with a processing temperature of 170 °C was selected for initial testing. Flat fiberglass samples were coated with a CB230 layer and evaluated for ease of laser machining and solderabilty. The metal coating on the samples was partially cured at 100-110°C to lower the laser fluence required for ablation. This "soft-cure" process did not affect its solderablity properties as a metal wire could still be soldered to the CB230 coating applied directly over glass. The CB230 paste was then applied over the entire exterior surface of the dome resulting in a metal layer of 100-150 microns thickness. To minimize oxidation, the coated domes were stored in vacuum until required. Future designs will incorporate a final environment-protective layer over the dome.

Laser-machining of the harder CB230 coating on top of a softer underlying substrate presented special challenges. The laser parameters must be chosen so that only the metal coating is removed while leaving the fiberglass relatively untouched. In practice, there was always some over-machining into the fiberglass surface due to thicker or more strongly adhered regions of the metal coating to the surface below. To minimize the over-machining, a protective 'primer' coating was first applied to the fiberglass before the CB230. This coating acted as a planarization layer for the rough fiberglass surface and served as a protective layer for absorbing some of the UV laser energy. However, it was later discovered that the primer layer considerably reduced the effective dielectric constant of the antenna feed structure and therefore was not applied to subsequent domes. Nevertheless, maintaining the laser fluence near or just above ablation threshold as well as using a focal spot with a more uniform intensity distribution are important in minimizing damage to the fiberglass.

The integration of the antenna and matching structure onto the surface of the dome required a slot-based design to give a broad, circularly-polarized radiation pattern for good reception over a wide range of orientations as shown in Fig. 3. The metal-coated fiberglass domes were laser machined to yield a conformal crossed-slot antenna fed by two

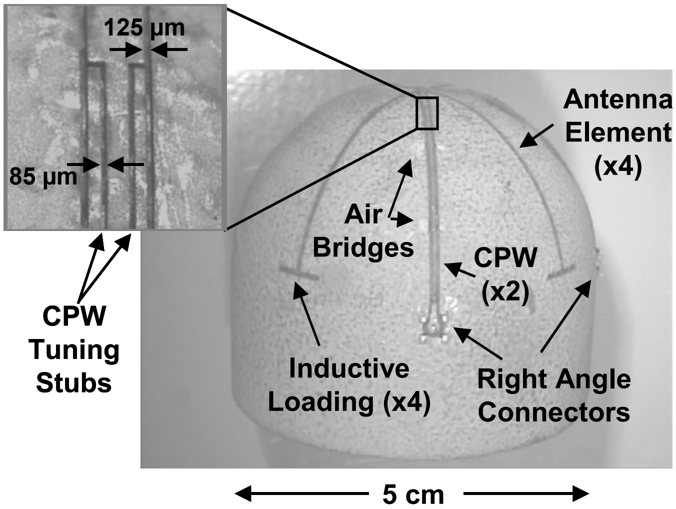

Fig. 3. Photograph of a prototype conformal crossed slot GPS antenna made by laser machining on a metal-coated fiberglass dome. A section of the tuning stubs for the CPW can be seen in the inset. Two sets of air bridges are also visible along the length of the CPW.

coplanar waveguide (CPW) transmission lines. The degree of roughness present in the surface of the fiberglass dome affected the uniformity by which the depth and width of the laser micromachined trenches could be controlled. To correct for these variations, the individual components of the antenna design were tested and then tuned by laser machining the required matching elements (inductive loading on the antenna slots, series stubs on the CPW).

The crossed slots are fed using two orthogonal CPW transmission lines oriented 45 degrees from the slots. CPW is used because it only requires one conductor plane and because its radiation loss can be minimized by the appropriate choice of dimensions and the use of air-bridges. The tuning stubs are implemented using series CPW shorted stubs placed inside the center conductor of the CPW feed line (see the inset in Fig. 3). The laser processing is critical to this approach, since it allows the implementation of these stubs with high precision in the very limited space available and over a curved surface as well. The CPW lines transition to female right-angle connectors that are mounted below the equator inside the dome, allowing connection to measurement equipment or to the receiver.

The initial design of the antenna was validated using a 3-D finite element modeling software package[8]. Fig. 4 shows both the simulated geometry as well as a sample set of radiation patterns. The patterns are typical of a curved or drooping crossed dipole, and show both good gain and polarization performance over greater than one hemisphere, allowing for greater variability in device orientation. A major challenge in the development of conformal antennas on composites is the lack of knowledge of material parameters. In these simulations, the material properties and dimensions were estimated to give a first order solution. In the actual fabrication of the antenna, the design and manufacturing steps are planned to allow tuning and the deduction of the material parameters as the machining progresses. The rapid prototyping ability discussed here is critical to this approach, as it allows quick and frequent machine/measure cycles that would be nearly impossible with other techniques.

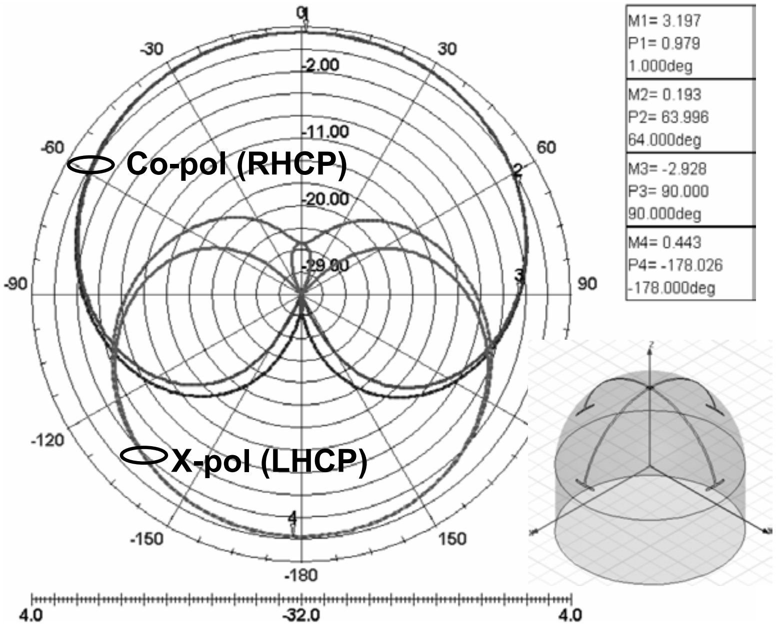

Fig. 4. Co- & cross-polarization radiation patterns (ϕ = 0, 90 cuts) calculated for the loaded crossed slots on the spherical dome shown in the inset (HFSS V9.0)[8].

3. RESULTS AND DISCUSSION

The fabrication of the antenna and associated feed structure on the dome consists of three steps. One of the CPW feeds is first machined and characterized. Then, the crossed slots are machined and tuned, and the second CPW added. Third, each CPW feed is matched by adding a series stub and then tuning its length.

The CPW feed lines are machined in incremental segments along a meridian of the dome, beginning near the equator and stopping just before the pole. For each segment, the effective dielectric constant ($\varepsilon_{r,eff}$) and the input impedance were calculated from the time (TDR) and frequency (S_{11}) data obtained from an HP 8510C network analyzer. For CPW's machined on similar domes, effective dielectric constants between 1.7 and 2.1 were measured, as were characteristic impedances between 70 to 80 Ω. Higher effective dielectric constants and lower impedances were expected based on previous measurements on planar substrates. It is thought that these results are primarily due to variations in the thickness of the conducting ink and to varying waveguide depth due to overcutting, and to a lesser extent to variations in the underlying material dielectric constant.

Once the first CPW feed is fully machined and characterized, the radiating elements (crossed slots) are machined into the surface of the dome. Matching the inherently high input impedance (> 300 Ω) of the slot elements to the 50 Ω system impedance requires the use of the series matching stubs mentioned above. To minimize the length of these matching stubs so that they fit, the slots are initially tuned to resonate below 1.575 GHz. To keep the slots small enough to fit on the dome, this tuning is accomplished by adding an inductive "hat" to the end of each slot as shown in Fig. 3 rather than by increasing their length. Care must be taken not to make these hats too large, however, as they can begin to affect pattern quality.

The final tuning of the antenna is accomplished by implementing a single-stub tuner in each CPW feed line. In this case, a short-circuited series stub offers the most compact solution, and the use of CPW allows the stub to be integrated directly into the center conductor rather than extending out over the rest of the spherical antenna ground plane (see Fig. 3). Due to the uncertainty in the electrical parameters of the tuning stub, its parameters were chosen to maximize its impedance and its length was incremented gradually to achieve the best match. A Smith chart showing the results of this incremental tuning is shown in Fig. 5. The chart is normalized to 50 Ω, and shows the input impedance of the antenna at the connector. Point 1 is the input impedance of the antenna before the addition of the matching stub. Points 2-7 show the effect of increasing the length of the stub; points 2 and 3 are increments of 12.7 mm each, and points 4-7 are incremental increases of 1.27 mm. The best match is obtained at Point 5, where the stub is 27.94 mm long (VSWR = 1.53). Ideally, the locus of points could be brought closer to the center of the chart by making the characteristic impedance of the CPW feed line closer to 50 Ω; the design could also be modified to take the actual impedance of the line into account.

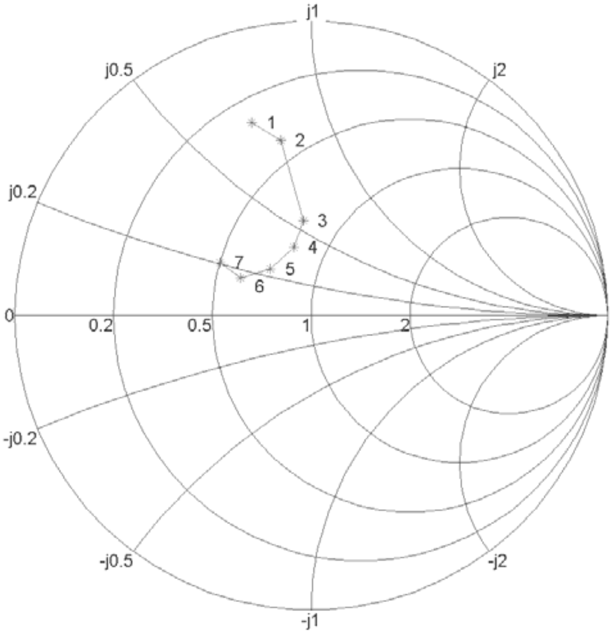

Fig. 5. Measured input impedance of the antenna for various series inductive stub lengths. Point 1: no stub. Point 2: 12.7 mm. Point 3: 25.4 mm. Point 4: 26.67 mm. Point 5: 27.94 mm. Point 6: 29.21 mm. Point 7: 30.48 mm.

This example shows the importance and inherent capability of our approach which allows the designer to quickly and iteratively modify and measure when design tools are rare and expensive, accurate data on materials is difficult to obtain, and normal fabrication methods are prohibitively expensive.

4. SUMMARY

Laser rapid prototyping has been used to fabricate a conformal crossed-slot antenna design and its associated CPW feed structures on a metal-coated fiberglass dome. Effective dielectric constants of 1.7-2.1 and characteristic impedances of 70-80 Ω were measured for CPW's machined on various domes. By tuning the length of a series-shorted stub, the best match of the input impedance of the antenna at the connector yielded a VSWR of 1.53. Current work is ongoing to help understand materials processing issues which will lead to improved antenna performance in the future.

ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research.

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