Design and Development of Aerogel-Based Antennas for Aerospace Applications

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Purpose

The purpose of this project is to develop aerogels with properties tailored to enable new antenna concepts with performance characteristics (wide bandwidth and high gain) and material properties (low density, environmental stability, and robustness) superior to the state of practice (SOP). A series of aerogels have been fabricated to characterize electromagnetic properties, including transmittivity, reflectivity, permittivity, and propagation losses. A prototype broadband planar patch antenna from down-selected aerogel formulations was fabricated and benchmarked against current antenna SOP.

Background

The design and optimization of communication system technologies in support of aerospace platforms is of paramount interest in the aviation industry, for government (e.g., NASA, DoD, etc.) and the commercial sector. Among the key technologies are transmit/receive (Tx/Rx) antennas required for communications (voice, high data rate video, internet, etc.) and navigation (GPS). A typical commercial and/or military aircraft (e.g., Boeing 737) could have as many as 15 to 100 antenna systems. This large number of antennas not only adds weight to the aircraft but also increases the complexity, and challenges the structural integrity of the fuselage. The latter is exacerbated in commuter and general aviation aircraft because of more limited space for antenna placement. Therefore approaches that could reduce the mass and number of antennas in the aforementioned aircraft and any other pertinent airborne platform (e.g., long duration, high altitude elevation platforms) without sacrificing performance are highly desired.

An innovative approach for lightweight antennas is to use aerogels which are highly porous solids with many interesting properties, including low density and low dielectric permittivity. The latter can reduce Radio Frequency (RF) losses and improve impedance matching in the antenna. We propose to develop antennas incorporating a robust new form of polyimide aerogel developed at GRC to address the challenges of reducing the mass and number of antennas, without sacrificing performance. The polyimide aerogels have superior mechanical strength over other types of aerogels and are easily fabricated into various forms as shown in Figure 1, making them enabling for this application. However, this project requires detailed knowledge of electromagnetic properties of the aerogels.

The work addresses innovative/visionary concepts for advanced communication systems in aeronautics aligned with: (1) Distributed and autonomous concepts for aviation systems, (2) Light weight materials and structural concepts.

Figure 1. Polyimide aerogels developed at GRC.

Use of durable aerogels will enable the design of lighter, wider bandwidth, higher gain, and even conformal antennas with potential for reduction of the number of antennas in aircraft and aeronautic platforms, reduction in mass and lower cost. The level of impact of mass savings will depend on antenna aperture size. Insertion of aerogels as components of planar patch antennas will enable wider operational bandwidths, reduce the number of antenna apertures required to support communication requirements, and reduce discontinuities in the aircraft fuselage. Flexible forms of aerogel can be explored in a Phase II effort as a foundation for conformal, drag-free "wrap-able" antennas. In addition, Earth Science remote sensing applications using unmanned air vehicles (UAVs), and LEO/GEO telecommunication satellites can also benefit from the proposed work, due to the advantages of using porous substrates in vacuum applications (less warping and out-gassing). The mass savings from fewer and lighter antennas could allow next generation aircraft/satellite designers to include additional payload electronics to enhance flying, navigation, and surveillance capabilities, or add more fuel to extend range or time aloft. The above is consistent with the ARMD goal for advances that improve aircraft and system efficiency.

Approach

Formulations of polyimide aerogels with different backbone chemistry were fabricated in sizes suitable for dielectric characterization at multiple bandwidths. RF characterization was performed to evaluate transmission and reflection properties, and electromagnetic losses at the operational frequencies of interest for polyimide aerogels. Formulations screened in the study include polyimide aerogels and polyimide-polyurea aerogels cross-linked with aromatic triamine and made using two different dianhydrides and mixtures of two diamines. Other properties of the polyimide aerogels (density, porosity, mechanical properties, etc.) are documented in publication 1 listed below. Properties of the polyimide-polyurea aerogels have not yet been published.

Based on the dielectric measurements, a down select to one formulation of aerogel was used as a substrate to fabricate a patch antenna and the performance was benchmarked against antennas made using SOP Rogers Duroid® 5880 and 6010 as substrates.

Summary of research

As laid out in the proposal, this project is divided into four tasks. A summary of accomplishments under each task is given below.

Task 1: Nine formulations of polyimide aerogels were fabricated in sizes needed for low frequency (~50 MHz), L-Band (~1.4 GHz), and X-Band (~12 GHz) measurements. Density, pore structure and mechanical properties of the aerogels were also characterized.

Task 2: The RF properties of the aerogels from Task 1, including dielectric constants and loss tangents, were measured over a range of frequencies.

Task 3: Based on measurements in Task 2, a down-selected aerogel formulation was fabricated and metallic coatings were successfully applied to the aerogels.

Task 4: Prototype patch antennas have been designed, fabricated, tested and benchmarked against current SOP. In addition, simulation studies were completed for different substrate materials and compared to antenna performance.

Accomplishments

The polyimide aerogels were fabricated from silicone molds and sanded to exact sizes needed for RF characterization at multiple frequencies. Dielectric constants at X-Band for some of the formulations are shown in Figure 2.

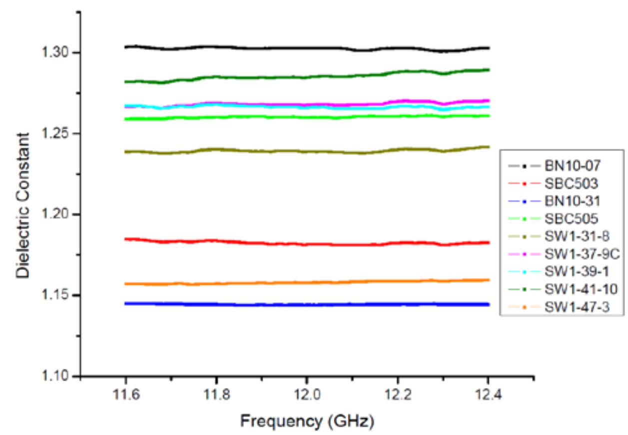

Figure 2. Dielectric constants at X-Band for various formulations of aerogels (average of two measurements).

In all frequency ranges measured, dielectric constants seem to track densities of the aerogels as shown in Figure 3, while the loss tangents are all pretty similar depending on frequency range. While backbone chemistry should also have an effect on dielectric constant, not enough formulations have been measured yet to differentiate the effect of backbone chemistry from the effect of density. Based on these measurements, the polyimide formulation chosen for further study was the sample labeled BN10-31 This formulation has the lowest dielectric constant, the best mechanical properties at the lowest density and good moisture resistance.

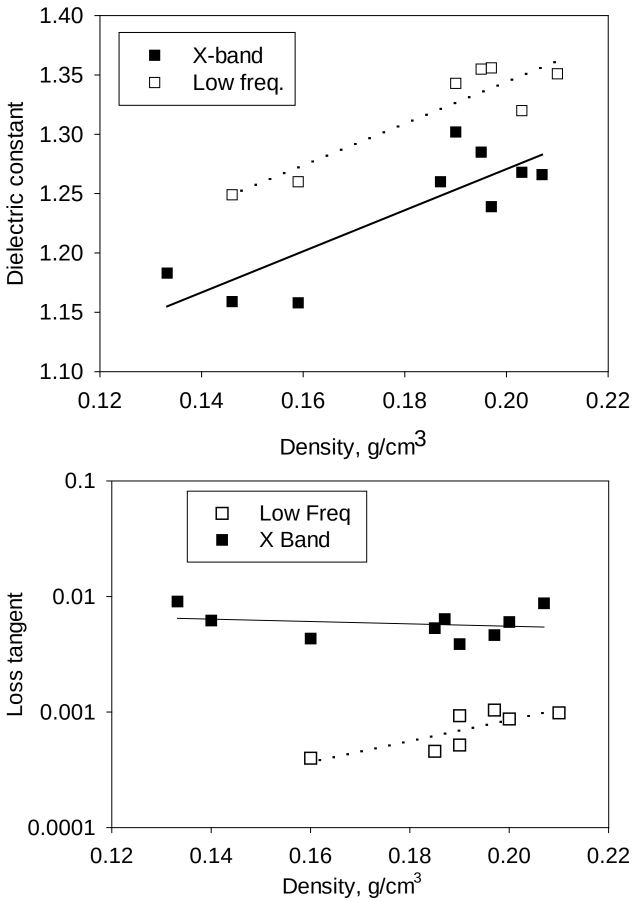

Figure 3. Dielectric constants and loss tangents of polyimide aerogels graphed vs. density.

One challenge to fabricating the aerogel patch antenna was thought to be applying a gold coating to the aerogel surface. As seen in Figure 4, this was accomplished by both e-beam evaporation and sputtering. In all cases, the gold adhered well to the surface and did not appear to cause any collapse of the pore structure or warping of the samples sized for X-Band measurements (2.29 cm x 1.02 cm x 0.74 cm).

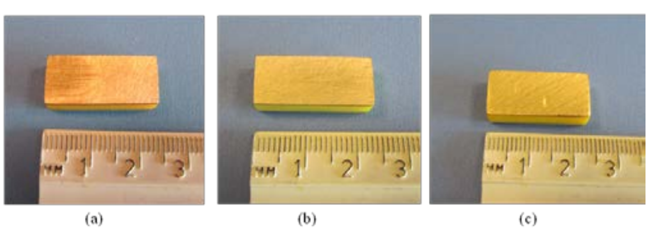

Figure 4: Metalized Aerogel samples: (a) e-beam evaporated gold (Au) (300 nm thick); (b) Sputtered Au layer (200 nm thick); (c) e-beam evaporated Au layer (2 µm thick).

Larger and thinner specimens of the aerogel were then fabricated for making the patch antenna. A schematic of the printed circuit patch antenna is shown in Figure 5. Figure 6 shows actual patch antennas fabricated using three different substrates: down-selected polyimide aerogel as well as the commercially available Rogers Duroid® 6010 and 5880. The aerogel antenna was fabricated with both the antenna and ground plane deposited with e-beam evaporated gold. Note that the aerogel substrate did warp slightly on application of the gold coating. The origin of this effect and how to suppress it are currently being investigated.

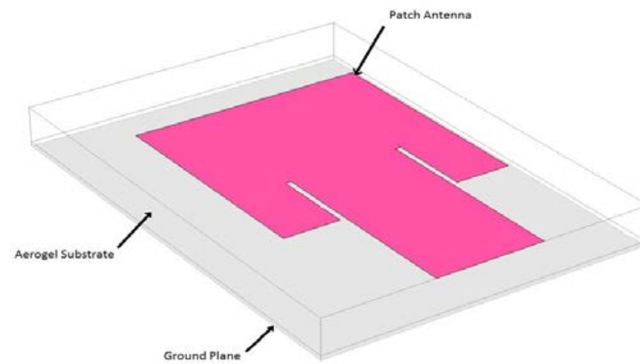

Figure 5: Schematic of printed circuit patch antenna on an aerogel substrate.

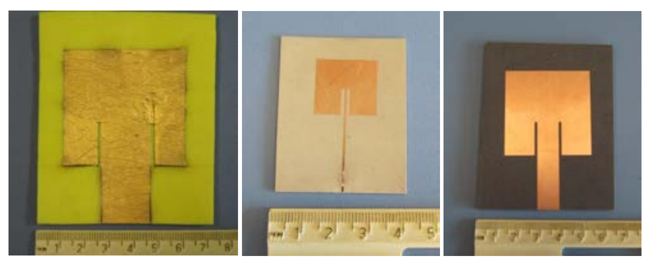

Figure 6: Photograph of patch antenna on polyimide aerogel substrate (left), Rogers Duroid® 6010 (ε_r=10.2) (center); and Rogers Duroid® 5880 (ε_r=2.2)(right).

Figure 7 shows a comparison of measured bandwidth and mass of the aerogel antennas with the Duroid antennas. It is worthwhile to highlight that the aerogel antenna exhibits both broader band width and lower mass than their Duroid® counterparts. In fact, the Duroid 5880 which is closer in bandwidth to the aerogel antenna has a total mass which is an order of magnitude higher.

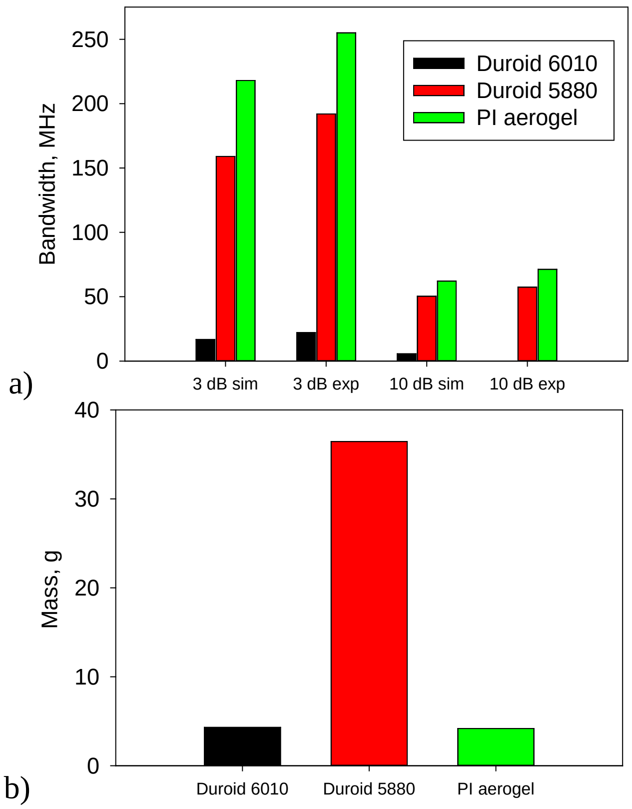

Figure 8: Comparison of a) bandwidth (experimental and simulated), and b) mass of antennas fabricated from polyimide aerogel, and Rogers Duroid® 6010 and 5880.

This confirms the potential advantages of the aerogel based antennas (ABA) antennas for aerospace applications as discussed in this proposal.

Next Steps

If funded in Phase II, we will explore antenna feeding approaches such as slot coupling that could lead to the optimization of the single element aerogel patch antenna. We will also further optimize the polyimide aerogel properties for better moisture resistance and lower density, as well as examine new backbone chemistries that may lead to lower dielectric properties. We will also examine other ways of fabricating the antennas including standard lithographic techniques and ink jet printing. We will also explore the scalability of the performance advantages observed with the single patch to the concept of phased arrays.

Applicable NASA Programs/Projects

In ARMD, the Unmanned Aircraft Systems (UAS), Next Generation Air Transportation Systems (NGATS) and National Airspace Capabilities programs may benefit from this effort. Earth Science remote sensing applications using unmanned air vehicles (UAVs), and LEO/GEO telecommunication satellites can also benefit from the proposed work.

Publications and Patent Applications

1. Peer-reviewed publication: Mechanically strong and flexible polyimide aerogels cross-linked with aromatic triamine. Mary Ann B. Meador, Ericka J. Malow, Rebecca Silva, Sarah Wright, Derek Quade, Stephanie L. Vivod, Haiquan Guo, Jiao Guo and Miko Cakmak, *ACS Applied Materials and Interfaces*, ASAP.
2. Novel Aerogel-Based Antennas for Aerospace Applications. Meador, Mary Ann B., Miranda, Félix A., Van Keuls, Frederick W., invention disclosure filed 12-23-2011.
3. Polyimide aerogel thin films. Meador, Mary Ann B. and Guo, Haiquan, patent filed 2-4-2012.
4. Low dielectric polyimide aerogels as a substrate for lightweight patch antennas. Mary Ann B. Meador, Sarah Wright, Anna Sandberg, Baochau N. Nguyen, Frederick W. Van Keuls, Carl H. Mueller, Rafael Rodríguez-Solís, and Félix A. Miranda, in preparation.

Awards & Honors related to Seedling Research

1. 2012 R&D 100 Award: Polyimide aerogels, Mary Ann Meador and Haiquan Guo.
2. NASA Exceptional Technology Achievement Medal 2012, Mary Ann Meador