

Slotted Polyimide-Aerogel-Filled-Waveguide Arrays

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Abstract— Polyimide aerogels were considered to serve as a filling for millimeter-wave waveguides. While these waveguides present a slightly higher loss than hollow waveguides, they have less losses than Duroid substrate integrated waveguides (less than 0.15 dB at Ka-band, in a 20 mm section), and exhibit an order of magnitude of mass reduction when compared to commercial waveguides. A Ka-band slotted aerogel-filled-waveguide array was designed, which provided the same gain (9 dBi) as its standard waveguide counterpart, and a slotted aerogel-filled-waveguide array using folded-slots was designed for comparison, obtaining a gain of 9 dB and a bandwidth of 590 MHz.

I. INTRODUCTION

Polyimide (PI) aerogels offer great promise as an enabling technology for lightweight aerospace antenna systems[1]. They are highly porous solids possessing low density and low dielectric permittivity combined with good mechanical properties[2]. While they have been aggressively explored for thermal insulation, barely any effort has been made to use these materials for microwave and millimeter-wave antenna applications that take advantage of their attributes. PI aerogels have mechanical properties that can make them useful in the design of waveguide components and antennas. Standard mm-wave waveguide sections have thick metal walls to provide mechanical stability; the wall thickness could be dramatically reduced if the waveguide was filled with a low-loss dielectric, since the mechanical stability would be provided by the dielectric filling. PI aerogels would be ideal fillings since their density is very low. This would provide very low mass waveguide sections and components, with reasonable loss, ideal for aerospace applications.

In this work, the use of PI aerogel waveguides for slotted waveguide arrays is examined, to take advantage of their mechanical and electrical properties for aerospace applications.

II. APPROACH

Several PI aerogel formulations were measured using an Agilent PNA E8361A vector network analyzer with the 85071E Materials Measurement Software at Ka-band, and the results were reported in [2]. The measurements were performed using the waveguide transmission method, and the samples thicknesses vary from 2.3 mm to 3.4 mm ($\lambda/4$ to $\lambda/2$ in the evaluated frequency range). Fig 1. shows the Ka-band electrical properties of a formulation of PI aerogel selected for

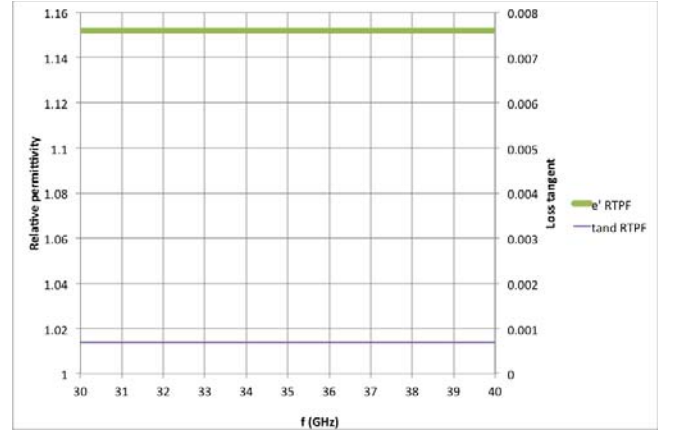


Figure 1. Measured electrical properties for PI aerogel formulation used.

this work. This formulation described in [2] as made from a mixture of 75 % 2,2-dimethylbenzidine and 25 % 4,4'-oxydianiline and biphenyl-3,3',4,4'-tetracarboxylic dianhydride in the polyimide backbone, exhibits a good combination of low electrical properties, low density and good mechanical integrity. These values, together with the aerogel density were used to calculate the waveguide losses and mass. We compared the losses and the mass for 20 mm waveguide sections at Ka-band, and used a standard WR28 waveguide with 1.016 mm thick Al 6061 walls as the reference.

Table 1. Mass and losses for simulated waveguides

Waveguide	Mass (g/m)	Loss at 37.5 GHz (dB/m)
Standard WR28	70.00	0.65
Aerogel filled	4.00	5.16
RT-Duroid 5880 SIW	6.98	8.54
Aerogel SIW	1.26	7.20

An aerogel filled waveguide was designed to have the same cutoff frequencies as the WR28 waveguide, with 2 μ m thick Au walls. In addition we designed two SIWs using Rogers RT Duroid 5880 (17 μ m Cu walls) and aerogel (2 μ m Au walls). Both SIW were designed to have the same cutoff

frequency for the TE_{10} mode as the WR28 waveguide. Table 1 presents a comparison of the mass and losses at Ka-band for a 20 mm section of the four simulated waveguides. At 37.5 GHz, the hollow WR28 waveguide has the lowest loss, as expected, followed by the aerogel filled waveguide, the aerogel SIW and the Duroid SIW, respectively. However, the mass of the standard WR28 waveguide is about 17.5 times the mass of the aerogel filled waveguide, and the mass of the Duroid SIW is 5.5 times the mass of the aerogel SIW. The mass savings in both cases are significant, and the aerogel waveguides have lower losses than the Duroid 5880 SIW. Since waveguide runs in aerospace vehicles are usually not very long, the mass savings more than compensate the incremental loss of the aerogel filled waveguide.

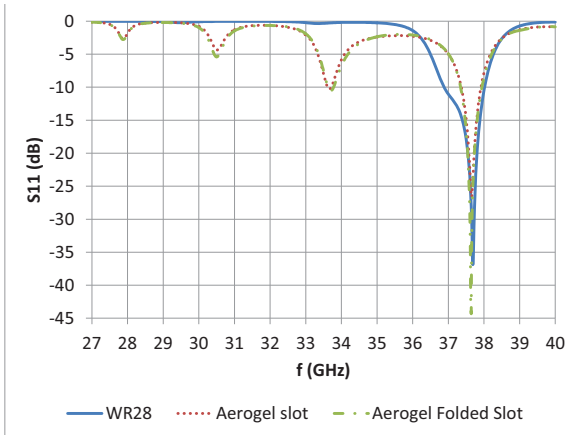


Figure 2. Return loss comparison for the three linear arrays

III. ANTENNA DESIGN

Three linear arrays were designed and simulated using Ansoft's HFSS, for operation at Ka-band. The designs were based on the paper by Orefice and Elliott [3]. The first array was a series-fed inclined slot array designed for the standard WR28 waveguide. This design was then adjusted for an aerogel filled waveguide with the same guided wavelength as the standard WR28 waveguide design. Since the filled waveguide lends itself to standard lithographic processes, a third array was designed, substituting the slots for folded-slots. Folded-slots can provide lower impedance and larger bandwidth than regular slots, and, to the authors' knowledge, have not been used in the design of slotted waveguide arrays. Table 2 shows

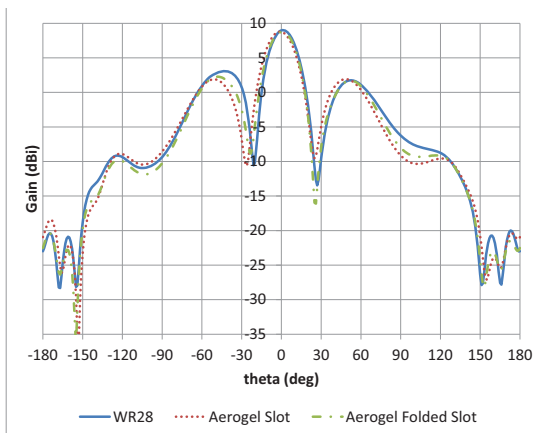


Figure 3. Gain comparison for the three linear arrays

the antenna dimensions for all designs, the l 's are the slot lengths starting from the feed end, the θ 's are the inclination angles, w_s the slot widths, and S_a the separation between slots in the folded slot antennas. Fig. 2 shows a comparison of the return loss, and Fig. 3 shows a comparison of the gain for all designs. The three arrays provide about the same gain (9 dBi), and have similar bandwidths, 540 MHz for the aerogel filled slot array and 590 MHz for the folded-slot version. This suggests a more detailed study of folded-slots for slotted array antennas is justified. The WR28 array shows a bandwidth of 1130 MHz. However, the savings in mass clearly make the case for the use of aerogel-filled waveguides for slotted waveguide array designs in aerospace applications.

Table 2. Antenna dimensions

Dimension	WR28	Aerogel Slot	Aerogel Folded Slot
l_1, l_4 (mm)	3.870	3.599	3.560
l_2, l_3 (mm)	3.863	3.592	3.554
$\theta_1, -\theta_4$ (deg)	19.67	19.67	19.67
$\theta_2, -\theta_4$ (deg)	-23.74	-23.74	-23.74
w_s (mm)	0.375	0.349	0.169
S_a (mm)	N/A	N/A	0.143

IV. CONCLUSIONS

Polyimide aerogels can provide an alternative filling medium for microwave and millimeter wave antennas in aerospace applications due to their very low density and excellent electrical and mechanical properties. They could be used to substitute Polytetrafluoroethylene (PTFE) and ceramic loaded substrates (e.g. Duroid) in applications where mass is of great importance. For waveguide applications, there are significant advantages in mass that more than compensate for the slightly higher loss of the aerogel filled waveguide, when compared to a commercial waveguide.

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