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AlN-based lossy ceramics for high average power microwave devices: performance–property correlation☆

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Abstract

AlN matrix-based ceramics were manufactured by hot pressing, with the objective of producing electromagnetically lossy materials in the 0.5–20 GHz region. These materials are designed to replace BeO–SiC lossy ceramics in high average power vacuum electronic devices to control electromagnetic instabilities, increase bandwidth, reduce reflections, and suppress unwanted modes. During the development of the candidate materials, complex permittivity measurements of samples were obtained using complex reflection, transmission, and cavity measurement techniques. Corresponding lossy buttons were bonded into klystron cavities and the resulting resonant frequency and cavity quality-factors were measured and compared with the measured material permittivity. Although trends could be established, the measured complex permittivity was not sufficient to completely predict the material performance in the cavities, due to large changes in cavity field distributions, material anisotropy, or uncharacterized metal-ceramic interface physics. High-power functional test results of AlN- relative to BeO-based materials and elevated temperature complex permittivity data of selected materials are presented.
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Keywords: AlN; Complex permittivity; Hot pressing; Lossy ceramics

1. Introduction

Microwave absorbing materials are widely used in vacuum electronic devices to suppress unwanted electromagnetic modes, prevent self-oscillation, enhance the bandwidth of resonant cavities, and provide matched electromagnetic terminations. Electromagnetically lossy ceramic materials based on a beryllium oxide (BeO) matrix have traditionally been the material of choice in high average power applications due to their high thermal conductivities. However, health issues related to the manufacture and use of BeO-containing materials have stimulated the recent development of less-hazardous replacement materials. Aluminum nitride (AlN) has been found to be an attractive alternative matrix material, combining a relatively high thermal conductivity with electronic properties similar to those of BeO.

Ideally, new AlN-based alternative materials should have dielectric properties that would enable them to be retrofitted into existing tubes with a minimum of mechanical re-design. To functionally assess the newly developed materials, an S-band klystron cavity (manufactured by Northrop Grumman, San Carlos, California) was used as the test vehicle. Historically, this high power cavity used machined buttons of BeO–SiC (Ceralloy® 2710, manufactured by Ceradyne, Inc. until 1996) bonded to the broadwall to achieve a specific resonant frequency and quality-factor (Q, related to bandwidth). The cavity is a particularly effective assessment vehicle as the frequency and Q can be measured with good accuracy and are highly sensitive to the geometry and electronic properties of the button materials; in addition, the same cavity can be tested with a high-average-power klystron to assess the power handling capabilities of the alternative materials. As described in the following sections, several candidate replacement materials based on AlN matrix were functionally tested, and their complex permittivities were measured using up to three different experimental techniques.

2. Experimental procedure

All tested materials were manufactured by hot pressing using aluminum nitride as the dielectric matrix, and

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conductive second phase additives based on transition metal carbides, nitrides or borides.[1] Code-identified billets with dimensions of approximately 10 cm×10 cm×1.5 cm, or 16 cm in diameter and 1.5 cm thick were produced. Initial screening of the materials was based on material densities and complex permittivities measured using an Agilent Technologies HP87050C coaxial probe and HP8720ES network analyzer (0.5–20 GHz range).

Promising materials were machined into right circular cylindrical loss buttons that were subsequently bonded into an S-band test cavity; in addition, rectangular and coaxial specimens were fabricated and used in test fixtures to measure complex permittivity, and pyramidal wedges were fabricated for X-band termination hot tests. Wherever possible, the same billet was used for all the samples in a given test series, and in all cases, the machining orientation (with respect to the hot pressing direction) of the samples was carefully monitored.

The complex permittivity of the materials was measured using three different techniques, as summarized in Table 1. Fig. 1 demonstrates WT sample orientation codes used later in the text.

Alternative materials with promising complex permittivities were machined into loss buttons and diffusion bonded onto the broadwall of the S-band test cavity by Northrop Grumman;[5] the volume of the loss buttons filled ~3.5% of the cylindrical cavity volume. The cavity resonant frequency (f) and quality-factor were measured under low-power excitation; further high average power testing was conducted on the S-band cavities and on X-band termination wedges by Northrop Grumman[5] to assess the power handling capabilities of the AlN-based materials.

Table 1
Complex permitivitty techniques

Method	Measured by	Frequency Range (GHz)	Sample geometry
APC-7 Coaxial; complex reflection measurement[2]	Naval Research Laboratory	0.3–18	Small disk, axis perpendicular to HP direction
WT Rectangular waveguide; complex transmission measurement[3]	University of Washington, Seattle	8–12	Rectangular thin plate. Orientation as specified
CP Cavity perturbation method[4]	Microwave Properties North	0.3–3	Small cylindrical rod, axis perpendicular to HP direction

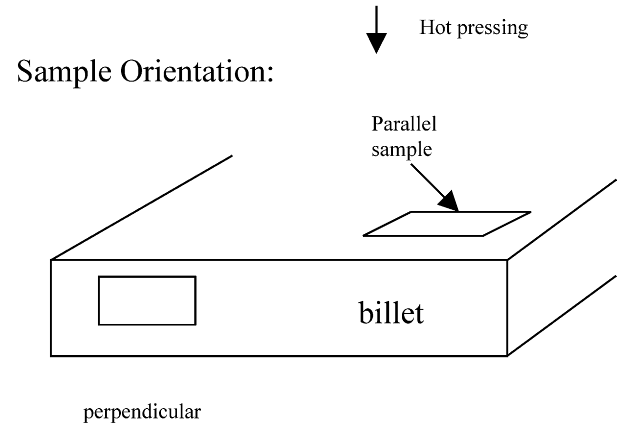

Fig. 1. Orientation of rectangular samples made for X-band permitivitty measurements (WT). Electrical field runs through the thickness of the sample (2 mm).

3. Results and discussion

Table 2 summarizes the measured S-band cavity Qs and resonant frequencies for a variety of alternative (AlN-matrix) material formulations. Material compositions were varied to achieve as close a match as possible to previous results using Ceralloy® 2710 BeO–SiC. As seen in the table, two material formulations—1374 and 137-CD1—had electronic properties sufficiently similar to Ceralloy® 2710 to effectively function as a drop-in replacement. With a thermal conductivity of 110 W/m-K (compared with 135 W/m-K for Ceralloy® 2710), the 137-CD1 formulation is suitable for high average power applications.

Figs. 2 and 3 display the measured real part of the complex relative permittivity and the loss tangent ($\varepsilon''/\varepsilon'$) for the 1374 and 137-CD1 materials. The data were taken over a frequency range of 0.1–18 GHz using all three measurement methods summarized in Table 1; as can be seen in the figures, there is a good correlation between the different measurement methods. It should be noted that the 137-CD1 material is mildly conductive at low frequencies. This is a desirable feature in

Table 2
S-band cold testing results after diffusion bonding loss buttons into the cavity[5]

Material	Resonant frequency (MHz)	Q	Thermal conductivity (W/m K)
Empty cavity	3452	>3000	n/a
2710 (BeO/SiC)goal	3400±10	62±10	135
13740Y	3404	86	55
137-CB	3411	110	105
1376	3434	24	80
1374	**3410**	**71**	**80**
137-CD	3414	97	110
137-CD1	**3405**	**72**	**110**

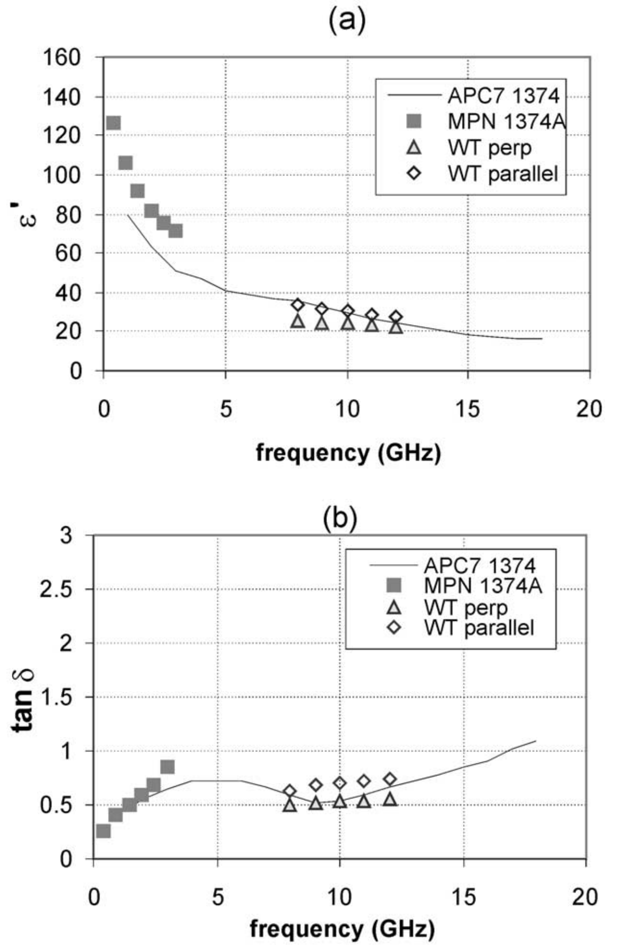

Fig. 2. Material 1374: measured real part of the relative permittivity and loss tangent from 0.1 to 18 GHz.

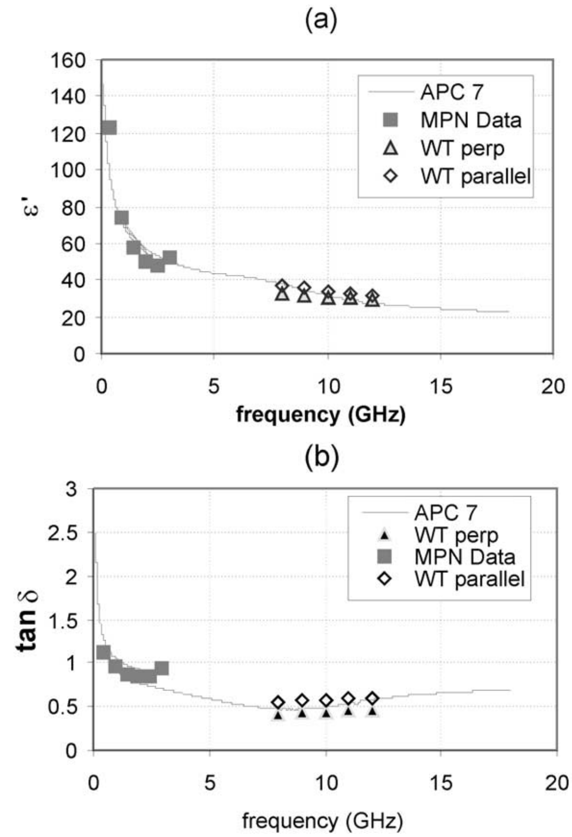

Fig. 3. Material 137-CD1: measured real part of the relative permittivity and loss tangent from 0.1 to 18 GHz.

microwave absorbing dielectrics for vacuum electronic applications as the dc conductivity will tend to dissipate surface charge build-up on the dielectric, inhibiting flashover and arcing. These differences in electrical conductivity have been confirmed by independent measurements.[6]

In both the 1374 and 137-CD1 materials, anisotropy of dielectric properties resulting from uniaxial hot-pressing is evident from the X-band rectangular waveguide (WT) measurements, where measurements were made on samples that were machined perpendicular and parallel to the press direction (Figs. 1–3). In both cases, the parallel samples had a higher real permittivity and loss tangent (by as much as 50%).

The changes of resonant frequency f and Q of the S-band cavity caused by the dielectric buttons in a mixed field region are produced by a sum of two effects. They produce at first glance, a rather strange behavior. A dielectric pellet with low or modest loss factor, located in a region of almost pure electric field, would produce a decrease in the cavity frequency as the value of ε' increases, reaching a limiting value of frequency shift as ε' became very large. In the same situation, the cavity Q would decrease as ε'' increases. However, in the present mixed field case, for values of ε' greater than 40, the frequency f actually increases with increasing ε', as seen in Fig. 4.

The frequency actually exceeds the empty cavity frequency (3452 MHz) for values $\varepsilon' = 130$ and $\tan\delta = 1.2$. At the same time, the cavity Q decreases as the loss tangent increases from 0.4 to 1.2, but the measured Q values are much lower than those predicted by formulations which only include the mechanism of dielectric loss in a pure electric field (i.e. the equivalent of lossy capacitor formulation). Both these effects can be understood by taking into account how the magnetic

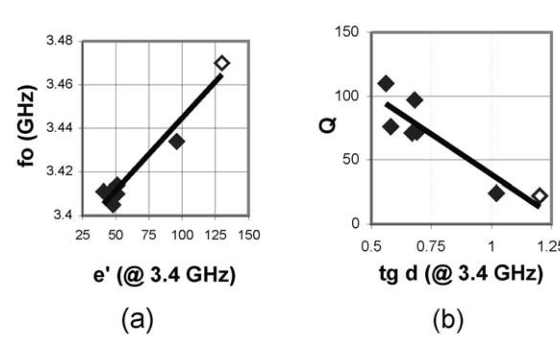

Fig. 4. Correlation between: (a) S-band cavity resonant frequency (f_0) and ε'; and (b) quality factor Q with the loss tangent.

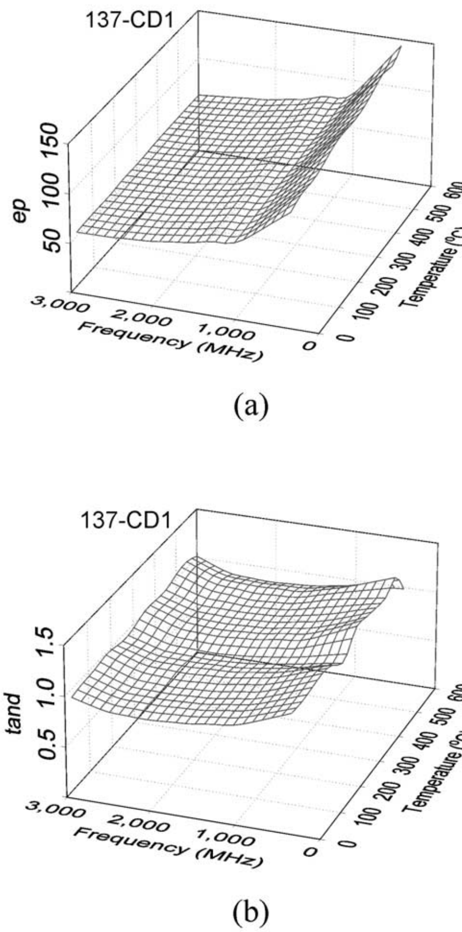

Fig. 5. Permitivitty temperature dependence for 137-CD1 sample (MPN data).

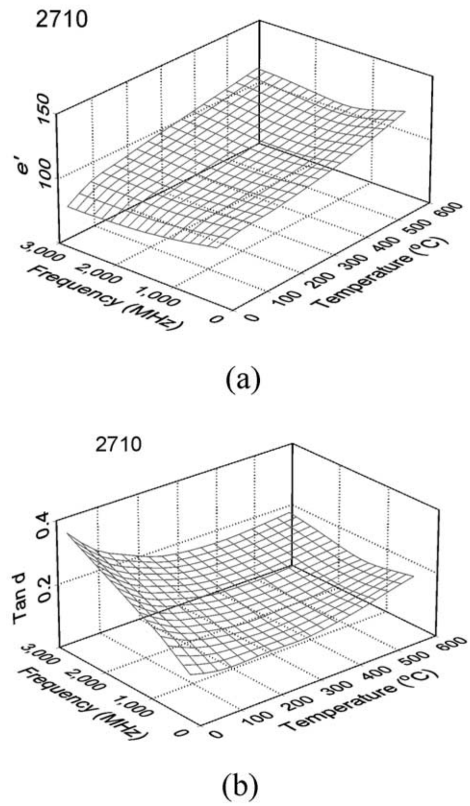

Fig. 6. Permitivitty temperature dependence for Ceralloy® 2710 sample (MPN data).

field and wall current distributions are influenced by the values of the "equivalent conductivity" of the pellet (proportional to ε'') and the skin depth, δ, the depth of field penetration into the pellet.[4] When the skin depth in the pellet material is much greater than the thickness of the pellet, then the presence of the pellet has very little influence on the surface currents in the copper and the azimuthal magnetic field. Only a very small amount of the surface current is shunted through the pellet as "equivalent conductive" current, to contribute to resistive losses. However, as the penetration depth decreases and is in the range of the pellet thickness, the surface currents are forced through the pellet (as opposed to traveling through the underlying copper), and the resistive losses are much higher, lowering the Q dramatically. For smaller values of penetration depth, the surface current flows increasingly over the exposed top of the pellet, excluding all fields from the pellet interior. This forcing of magnetic field out of the pellet volume causes an increase in frequency, which for the case of $\tan\delta \sim 1.2$ shown on Fig. 4, actually brings the cavity frequency above the empty cavity frequency.

Because of this complex relationship, it will only be possible to accurately predict the effect of the buttons on the cavity response using a full 3-D electromagnetic code that includes full material properties in the calculation. In the present case, functional testing in a realistic cavity was considered the most reliable method to chose a replacement material.

Material 137-CD1 shows minimal permittivity temperature dependence up to 600 °C in the 0.3–3 GHz range (Fig. 5). This is in contrast to BeO–SiC lossy materials which show a significant increase in ε' and a decrease in loss tangent as temperature increases,[6,7] as shown in Fig. 6.

Based on the promising low-power test results summarized in Table 2, materials 1374 and 137-CD1 were also subjected to high-power tests in both S-band (button-loaded cavity) and X-band (broadband termination wedge). All hot testing was performed by Northrop Grumman.[1,5] Both materials performed well during the tests, exceeding the minimum acceptable power handling standards required by Northrop Grumman; the test results are summarized in Table 3. The average power handling capability of the materials was consistent with their measured thermal conductivities. Material 137-CD1 performed especially well in the S-band hot tests; based on its performance, it should be capable of replacing Ceralloy® 2710 in this klystron application.

Table 3
X-band and S-band hot test performance[1]

Material	X-band power capability (kW)	S-band power capability (kW)	
	Average	Average	Peak
Target	0.50	0.50	150
Ceralloy® 2710	1.03	1.76	504
1374	0.40	–	–
137-CD1	0.78	1.16	333

4. Conclusions

It has been demonstrated that materials can be developed to match the behavior of another material in a specific microwave tube application (S-band), and to perform at high power. Unfortunately, this process is not a simple function of complex permittivity data obtained using the APC-7 method, the only method giving the results in the correct frequency range. Demonstrated anisotropy in dielectric properties and limited electrical conductivity of the materials contribute to the complexity. Functional testing will be a requirement until accurate 3-D codes are developed to account for all the effects.

The complex permittivity data obtained using three different measurement techniques show a reasonable mutual agreement and confirm the trends between samples. The 137-CD1 material, which performed as a drop in replacement for Ceralloy® 2710, also shows temperature independent dielectric properties up to 600 °C.

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