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Evaluation of Ultem 1000, 1010 and 9085 for Radome Applications at 24.5 GHz

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Abstract

The UAS in the NAS project Flight Test 6 (FT6) campaign scheduled for FY19Q3 will evaluate the proficiency of a Honeywell DAPA-Lite Radar installed on a Tiger Shark unmanned vehicle to detect the presence of air traffic operating in its vicinity. A 3D printed radome will be manufactured for the front of the Tiger Shark to enclose the radar during FT6 operations. The DAPA-Lite radar operates in the 24.5 GHz frequency band. Material properties of 3D printer filaments are widely available for the mechanical and thermal properties, but limited knowledge exists on the electrical properties for radome applications and no data was found to correspond at the 24.5 Ghz frequency band. To minimize project risk associated with the radome performance, transmissivity and reflectivity measurements were conducted on two candidate 3D printed dielectric material filaments (Ultem 1010 Natural and Ultem 9085 Black) and two thicknesses of a solid laminate (Ultem 1000) material. The 3D printed Ultem coupons were tested shortly after being printed and again 8 months later to examine ageing effects of the open cell structure. This paper presents the transmissivity and reflectivity measurement results collected on the Ultem coupons and concludes the 3D printed 1010 Natural coupon is a suitable candidate filament for radome applications at 24.5 GHz. The design of the structure's open cell matrix has a significant impact on the material's surface reflectivity.

Introduction

To ensure the UAS in the NAS Flight Test campaign detect and avoid radar will function properly behind the 3D printed radome, the radar/radome system should be characterized across its expected operational field of view. The UAS in the NAS FT6 operations will utilize the Honeywell DAPA-Lite radar unit. The radar is currently under development and was not available to conduct a system level performance evaluation. A 3D printed radome has been proposed to house the DAPA-Lite radar in the nose of the NASA Armstrong Tigershark UAS. To achieve some level of confidence an acceptable 3D printed filament is chosen for the radome manufacturing, transmission and reflection measurements were conducted to evaluate the electrical performance of two candidate 3D printed filaments and one solid laminate.

Optimum radome performance can only be achieved if the radome material appears transparent to the radar signal. The radar signal transmission thru a radome material is influenced by the amplitude and phase of the reflections occurring at the free space/front surface and back surface/free space boundaries. The transmitted power is further reduced by the signal absorption or attenuation of the radome material. Maximum operational radar range is only achieved if the radome properties have minimal impact in reducing the total power of the transmitted signal. Transmissivity and reflectivity measurements are thus key indicators of the expected radome performance.

A total of 3 different Ultem materials were examined. Two 5 inch square, ¼ inch thick Ultem 9085 black filament coupons manufactured at NASA Ames, two 5 inch square, ¼ inch thick Ultem 1010 natural filament coupons manufacutured at NASA Langley, and two solid laminate Ultem 1000 coupons were measured to deterimene the transmissivity and reflectivity of the materials. The ¼ inch thick coupons are approximately a half wavelength at 24.5 Ghz. This is an ideal thickness for radome materials and allows the reflections from the front surface and back surface to be out of phase resulting in better transmission through the material. Radome thicknesses of less than a tenth of a wavelength also generally perform very well. Radome thicknesses of more than a tenth of a wavelength up to about a half wavelength do not perform as well. The Ultem 1000 solid laminate coupons were 0.06 inch and 0.125 inch. The coupons were 6 inches wide by 7 inches long. For comparison purposes, a commercially available radome was also measured along with the NASA 3D printed coupons to provide reference data to a radome material known to work well for this application.

Nomenclature

dB	decibels
ETR	Experimental Test Range
GHz	Giga Hertz
MHz	Mega Hertz
NAS	National Air Space
NASA	National Aeronautics and Space Administration
PNA	Programable Network Analyzer
RF	Radio Frequency
S11	Reflection Coefficent
UAS	Unmanned Arieal System

Experimental Setup

The measurements were conducted in the NASA Langley Experimental Test Range (ETR) using an Agilent Programmable Network Analyzer (PNA) operated in the S11 reflection coefficent mode with software gates enabled. The S11 mode only requires one antenna to transmit and receive the radar signal. Software gates were used to limit the received signals to capture only the reflections occurring at the material coupon surfaces. This approach was successful at removing the large reflections from the impedance mismatch occurring at the RF cable connection and waveguide feed adapter. The PNA was calibrated using an open, load, short technique, but this calibration approach was not effective or beneficial at providing absolute measurement values and was not used. Even though absolute values were not obtainable, the data is valid for reference comparisons between the coupons and to a commercial radome which is known to work well for a 24.5 GHz radar.

Two Ultem 1010, two Ultem 9085 and two Ultem 1000 coupons were measured. Each coupon was measured in two orthogonal directions relative to the incident E field by rotating the coupon 90 degrees to examine any potential polarization affects. The coupons were also flipped over to the opposite side facing the incoming signal to explore differences between the top side versus the bottom side. The coupon top side was identified as having a pronounced ridge at the outer edge perimeter and was much shinier than the opposite side. This resulted in a total of 4 measurements for each of the 6 coupons; top side, top side rotated 90 degrees in the E plane, bottom side and bottom side rotated 90 degrees in the E plane. The S11 reflectivity measurements for the Ultem 1010 and 9085 coupons were repeated 8 months after the initial tests were conducted to examine ageing effects.

To evaluate the coupon's transmission performance using the S11 mode, a metal plate was measured in conjunction with the material coupon to ascertain the coupons' absorptive properties. The metal plate was measured once by itself to obtain a baseline comparison, then with the coupons measured under the metal plate. In theory, the metal plate will reflect all the signal back thru the coupon. Best practices were used to size the metal plate to ensure it extended many wavelengths beyond the aperture perimeter to minimize edge diffraction effects. Any measureable differences between the metal plate measurements and the coupon/metal plate measurements are attributed to the two way path loss attenuation.

Frequency domain reflection and transmission measurements were collected by placing the coupons directly over the aperture of a Sage SAR-2507-42-S2 horn antenna. The antenna aperture dimensions measured 4.27 inches wide by 3.41 inches long. The reflection at the antenna aperture was approximately 5 dB lower than the reflections from the coupons and did not significantly impact the measurement results. Due to the size of this antenna's aperture, the commercial radome material could not be adequately assessed. Figure 1 shows the Sage antenna with the Ultem 1010 coupon and metal plate over the antenna aperture.

A second test configuration was developed to collect time domain and frequency domain reflection and transmission measurements using a DHG SAS-574 dual ridge antenna. The antenna aperture dimensions measured 1.2 inches wide by 1.6 inches long. The smaller aperture was of sufficient size to enable the measurement of the commercial radome. The material coupons and commercial radome were placed directly on top of the antenna aperture for measurement. The reflection occurring at the cable/waveguide adapter connection was close enough in time to the aperture response to require a measurement subtraction to improve the quality of the data. This was accomplished by collecting data without the coupon and vector subtracting this data from the coupon measurements.

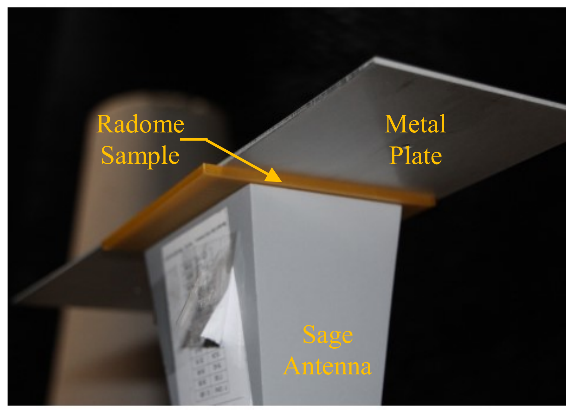

Figure 1. Ultem 1010 and metal plate covering Sage antenna aperture for transmission measurement.

A third test configuration was developed to create a 3.5 inch standoff distance between the antenna aperture and the coupons to better represent a potential implementation of the 3D printed radome installation on the Tigershark. The same SAS-574 antenna was used for the standoff measurements. A hollow polyethylene open cell foam support enclosure was placed around the horn allowing several inches of free space separating the horn aperture from the surrounding foam support as shown in Figure 2. The top of the foam support was 3.5 inches higher than the aperture of the antenna. This created a 3.5 inch standoff separation distance between where the coupons were measured and the antenna aperture. The coupons were centered over the aperture as best as practical. Repeatability measurements indicated no measureable differences could be detected from the small variations in center placement over the hollow enclosure. For this test their existed enough separation between the coupon response and the cable/waveguide adapter response to not require the subtraction method. The response was software gated as before to isolate the response of interest.

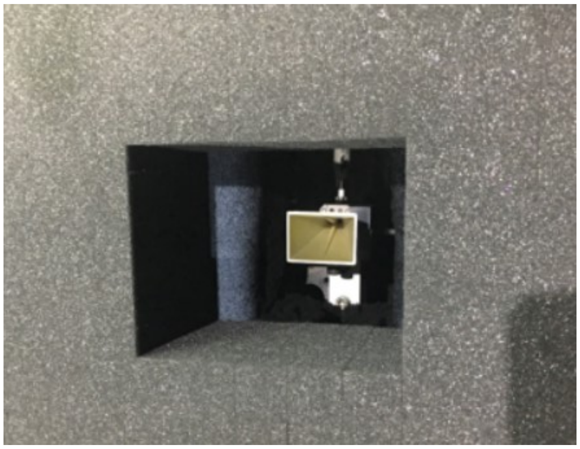

Figure 2. Test Configuration 3 showing the SAS-574 Antenna and Polyethylene Foam Support Enclosure.

Measurement Results

S11 frequency domain reflectivity data collected on the two Ultem 1010 coupons using the Sage SAR-2507-42-S2 horn antenna are shown in the plot in Figure 3. Figure 4 presents data for the Ultem 9085 coupons using the same test configuration. The coupons were measured in the 4 orientations as described above. The curve label identifies the coupon being measured and its orientation. “1c” or “2c” indicate the Ultem clear 1010 coupons. “3b” or “4b” indicate the Ultem black 9085 coupons. These labels are followed by “t” for top or “b” for bottom. The trailing digits in the nomenclature of “0” or “90” refer to the coupon position orientation relative to the E plane. “1ct0” would indicate the data curve for the Ultem clear 1010 coupon 1 measured on the top side with the sample oriented at 0 degrees reference to the E plane. Reflection data measured 8 months after the initial data was collected is denoted with a “r” at the end of the naming convention. The coloring convention in the plots are consistent across all data sets. Solid lines are shown for measurements on the top side. Dashed lines show measurements from the bottom side. Coupon one is dark red, two is green, three is blue and four is dark blue. If the coupons are rotated 90 degrees, the color convention changes to yellow, light green, light blue and purple for coupons 1 thru 4 consecutively. The frequency response curves of the two Ultem 1010 coupons in Figure 3 show very similar results for the 4 test positions at 24.5 GHz. The knee of the curve occurs at the frequencies where the coupon thickness approaches a half wavelength to cause cancellation between the front and back surface reflections.

Frequency domain reflectivity data for the two Ultem 9085 coupons are shown in figure 4. The 8 curves align fairly well at 24.5 GHz, but significantly vary at the knee of the curve between top side and bottom side. The vertical scale is expanded to show the dramatic change at the knee of the curve where the thickness of the coupons approach a half wavelength. The overall relative reflection amplitude is about the same for the Ultem 9085 and Ultem 1010 coupons at 24.5 Ghz.

The measurements were repeated 8 months after the initial data was collected on the Ultem 1010 and 9085 coupons to examine potential ageing effects caused by coupon deformation and moisture ingress in the open cell structure. Figure 5 presents the frequency domain reflectivity data for coupon 1 as previously shown in Figure 3 along with data collected 8 months later on the Ultem 1010 using an identical test setup. The 8 month data is noted with an “r” at the end of the label, and symbols have been added to the data curves to help distinguish the data sets. Even though the 8 month data curves behave similarly to the original data, the minimum amplitude in the 8 month curves have shifted about 100 MHz higher in frequency indicating a physical change in the coupon has occurred. At 24.5 Ghz, the reflection coefficient is a couple dB lower than the original data. Figure 6 presents the frequency domain reflectivity data for coupon 2 as previously shown in Figure 3 along with data collected 8 months later on coupon 2. The data shows a similar trend as was observed in Figure 5 for coupon 1 suggesting both coupons underwent a similar change.

Figures 7 and 8 present the frequency domain reflectivity data for Ultem 9085 coupons 3 and 4 shown in Figure 4 along with data collected 8 months later. The 8 month data shows a similar trend as was observed for the Ultem 1010 coupons. The minimum amplitude in the 8 month curves have shifted about 100 MHz higher in frequency indicating a physical change in the coupon has occurred. At 24.5 Ghz, the reflection coefficient is again a couple dB lower than the original data for both coupon 3 and 4.

S11 frequency domain reflectivity data collected on 0.06 inch and .125 inch thick solid laminate Ultem 1000 coupons using the Sage antenna are shown in the plots in figures 9 and 10. “5l” corresponds to the 0.06” thick solid laminate Ultem 1000 coupon. ”7l” corresponds to the 0.125 inch thick solid laminate Ultem 1000 coupon. The same 4 coupon orientations were measured. Figure 9 shows the reflection coefficient for the 0.06” thick Ultem 1000 coupon at 24.5 GHz measures around -20 dB. This is approximately 18 dB higher than the corresponding Ultem 1010 coupons. Figure 10 shows the reflection coefficient for the 0.125 inch thick Ultem 1000 coupon at 24.5 GHz measures around 5dB lower than the Ultem 1000 0.06 inch thick coupon. The Ultem 1000 solid laminate is a homogenous material and thus is not expected to have reflection coefficient differences based on coupon orientation. The laminate coupons were not perfectly flat and did not lay on top of the Sage antenna aperture as well as the 3D printed coupons had. The slight differences in reflection coefficient in relation to coupon orientation is attributed to the coupons not lying flat on the antenna aperture. The Ultem 1000 coupons were also measured beneath a metal plate to determine the attenuation of the material, but because the coupons did not lay perfectly flat the data results were skewed and thus will not be reported.

The second test configuration used the DHG SAS-574 dual ridge antenna to collect time domain and frequency domain reflection and transmission measurements on coupons 1 and 3. The top and bottom sides were measured at 0 degrees rotation relative to the E plane. A commercial radome was also measured. Figure 11 presents the frequency domain reflection data plots for these 5 measurements. The reflection from the commercial radome is almost 5 dB higher than the Ultem coupons at 24.5 GHz which would indicate the reflection from the Ultem materials should be within acceptable bounds for radome operation. The thickness of the commercial radome is believed to be about a tenth of a wavelength. The data curve is more linear across frequency and does not exhibit the characteristic knee response as seen with the half wavelength thick Ultem coupons.

Figure 12 presents time domain reflection data for the front and back of the same 2 coupons and commercial radome. The commercial radome time domain reflections are a little higher in amplitude than the Ultem coupons and appear as a single point reflection due to close proximity of the front and back surfaces. The Ultem 1010 coupon displays similar time domain responses between both top and bottom orientations. The Ultem 9085 coupon shows a significant change in the first reflection based on the top or bottom coupon orientation.

Figure 13 presents the time domain response of the transmission measurements on the Ultem 1010 coupon 1 and Ultem 9085 coupon 3 compared to a metal plate response. The offset response in time of the metal plate compared to the coupon/metal plate measurements correlates to the thickness of the coupons. The time domain response shows less than a tenth of a dB two way path loss. This is a reasonable loss for a radome.

The third measurement test configuration used the same DHG SAS-574 dual ridge antenna with a 3.5 inch standoff distance between the antenna aperture and the coupons. Frequency domain reflection and transmission measurements on coupons 1 thru 4 in all 4 orientations were collected. Figure 14 presents the frequency domain reflection data plots for the 16 measurements. The curves align fairly well at 24.5GHz except for a notable difference from the Ultem 9085 coupons measured from the back side. All 4 of these measurements fall outside the track of the other 12 measurements at 24.5 GHz. The Ultem 9085 has shown more significant inconsistencies in the reflection response between the front side and back side as compared to the Ultem 1010. This suggests manufacturing deviations in the 3D printing could impact the expected performance more significantly than with the Ultem 1010. For this reason the Ultem 1010 is recommended as a better choice for radome applications.

Figure 15 presents the frequency response of the transmission measurements on the Ultem 1010 coupons compared to the metal plate response. The Ultem 1010 shows a maximum two way path loss of about a quarter dB at 24.5 GHz.

Conclusions

To minimize project risk associated with the FT6 radome performance, transmissivity and reflectivity measurements were conducted on two candidate 3D printed dielectric material filaments (Ultem 1010 Natural and Ultem 9085 Black) and two thicknesses of a solid laminate (Ultem 1000) material. The dielectric coupons were characterized using a PNA in the S11 mode at the NASA Langley ETR facility. Coupon measurements can provide an indication of the expected radome performance at normal incidence. To obtain off normal incidence characterization, the radome would be tested with the radar over the full field of view. Since neither the radome nor the radar were available for testing, only coupon measurements were used to conduct this study.

The data results indicated the Ultem 1010 Natural material showed acceptable performance and no notable polarization effects when the coupons were flipped front or back and rotated 90 degrees to the E field. The Ultem 9085 coupon showed significant differences in the front side surface reflections compare to the back side reflections. The open cell matrix used to manufacture the structure has a stong influence on the level of the surface reflection. The solid laminate Ultem 1000 coupons showed a much higher reflection coefficient than the Ultem 1010 coupons. For these reason it is recommended the Ultem 1010 filament be selected over the solid laminate Ultem 1000 and Ultem 9085 filament. The Ultem 1010 coupon measurements collected 8 months after the initial tests indicated a physical change in the open cell 3D printed material but the reflection coefficient at 24.5 GHz still meet expected performance levels.

It should be noted the open structure of the 3D printed material layers could be prone to moisture ingress and impede the radome performance. If high humidity conditions exist for the FT6 flight campaign, a moisture resistant thin film coating should be applied to the radome surfaces.

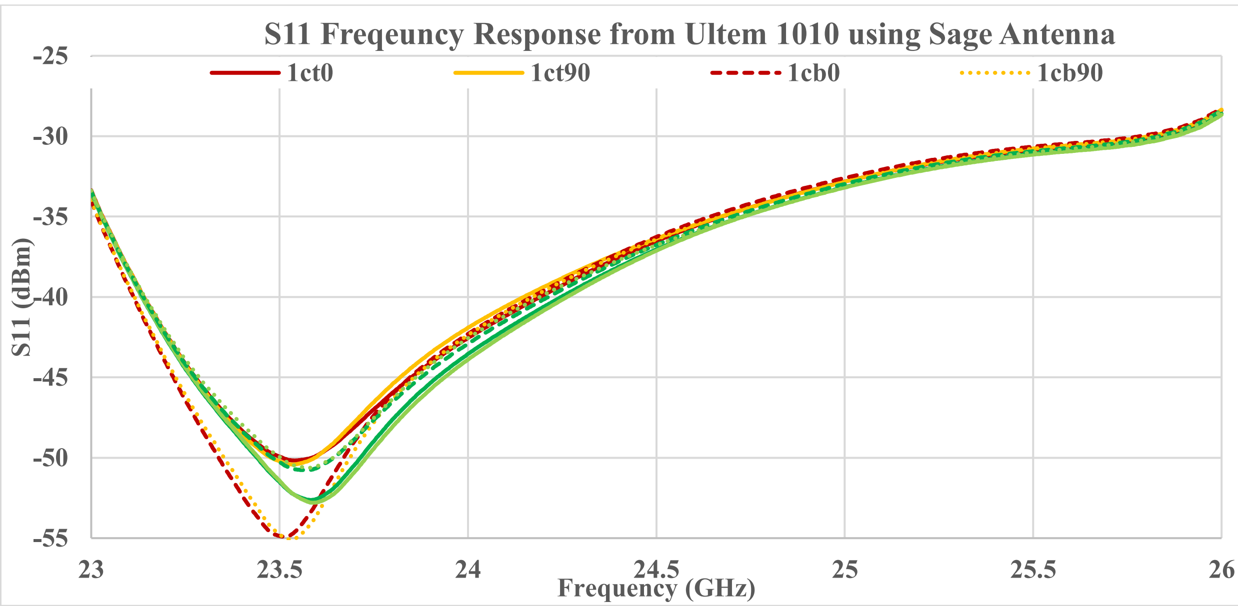

Figure 3. S11 Frequency Response of Ultem 1010 using Sage Antenna.

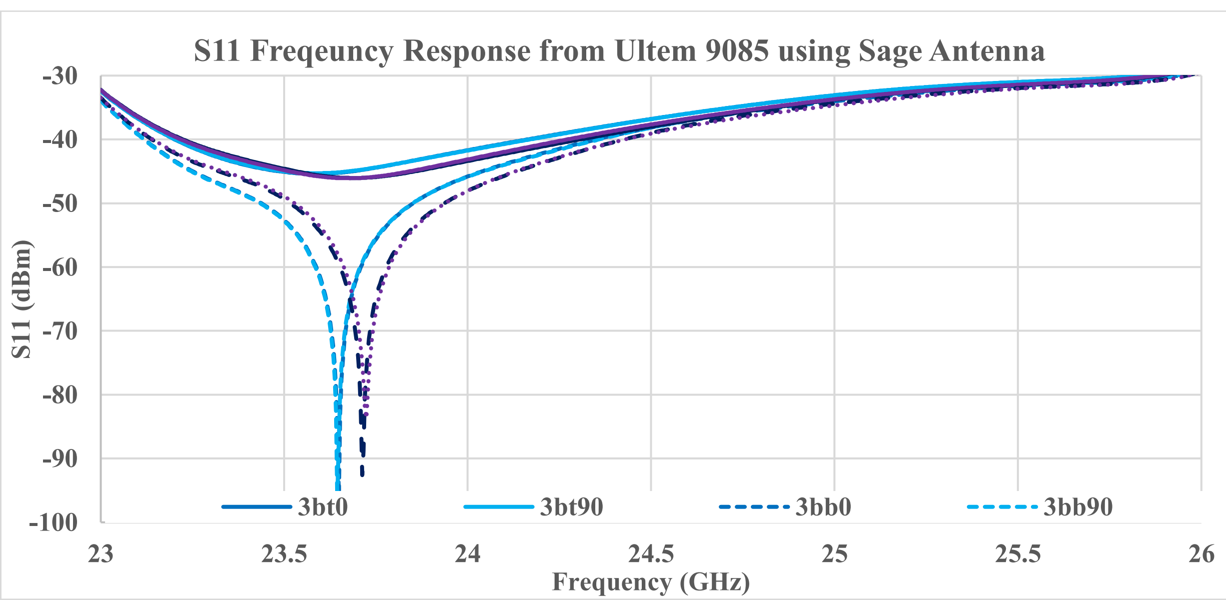

Figure 4. S11 Frequency Response of Ultem 9085 using Sage Antenna.

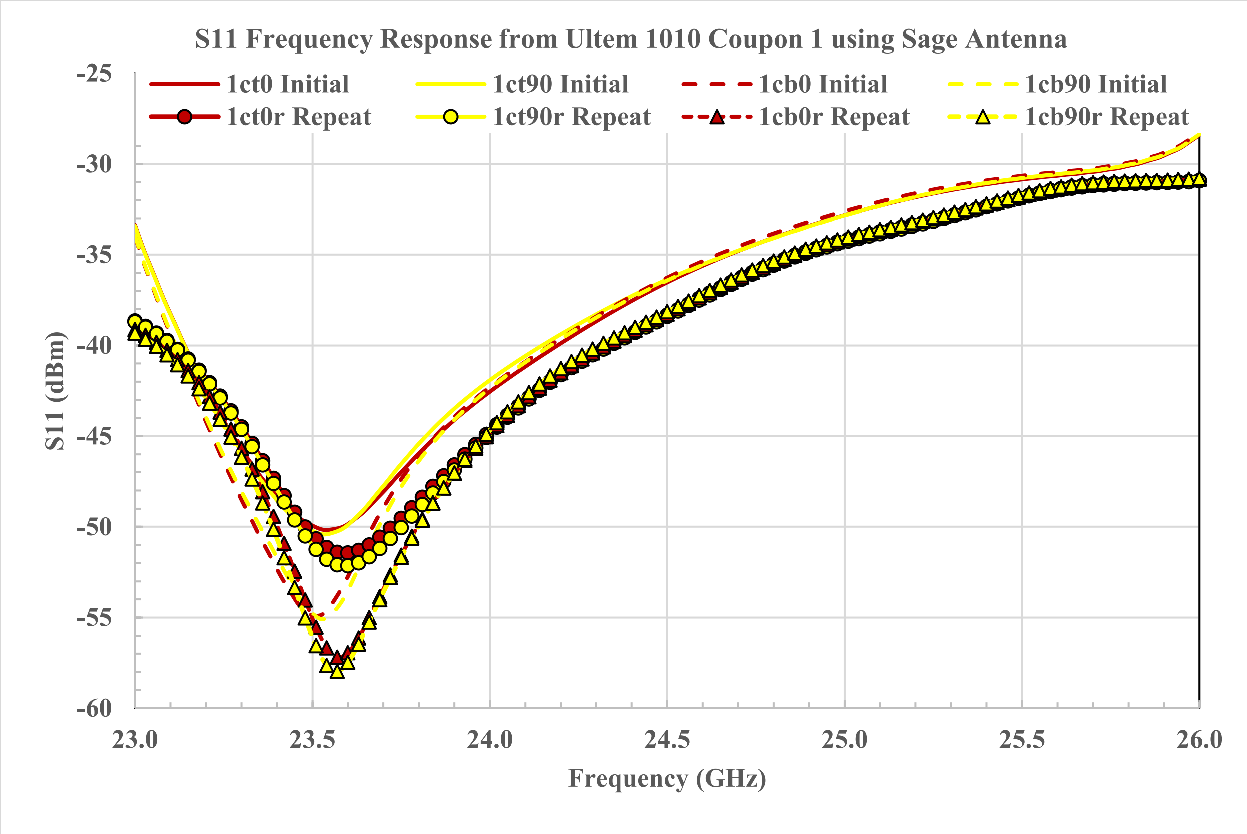

Figure 5. S11 Frequency Response of Ultem 1010 Coupon 1 after 8 months using Sage Antenna.

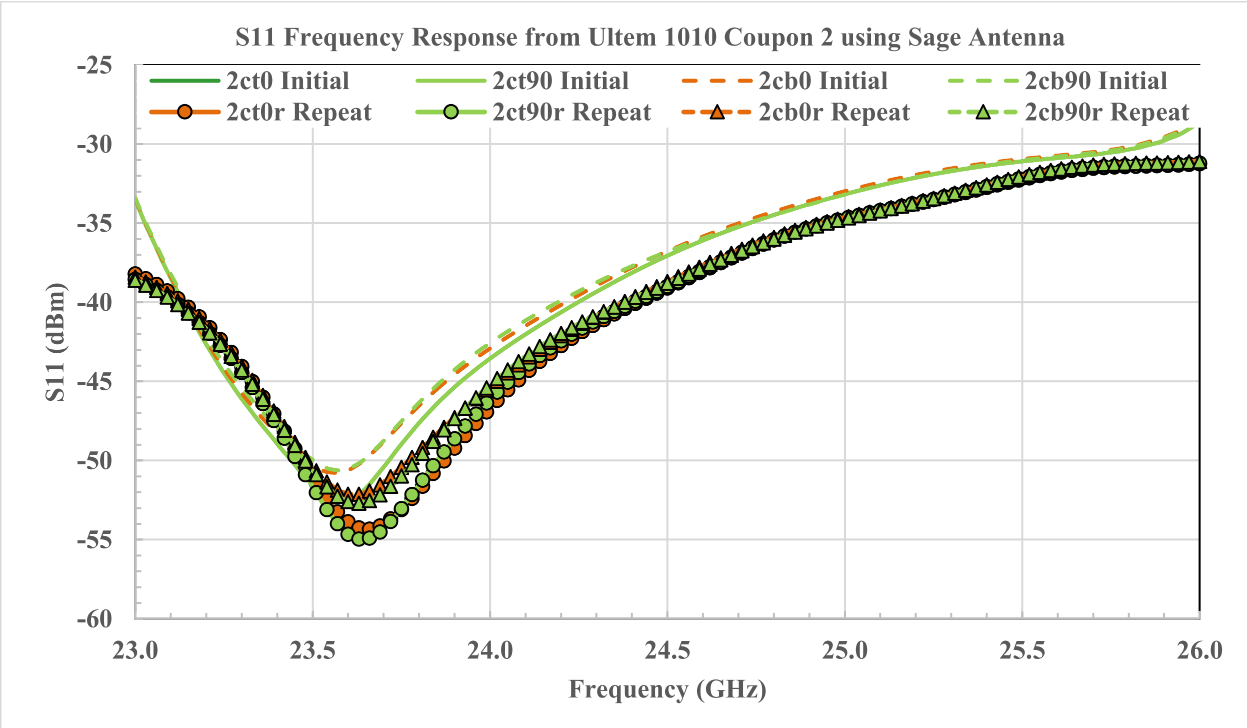

Figure 6. S11 Frequency Response of Ultem 1010 Coupon 2 after 8 months using Sage Antenna.

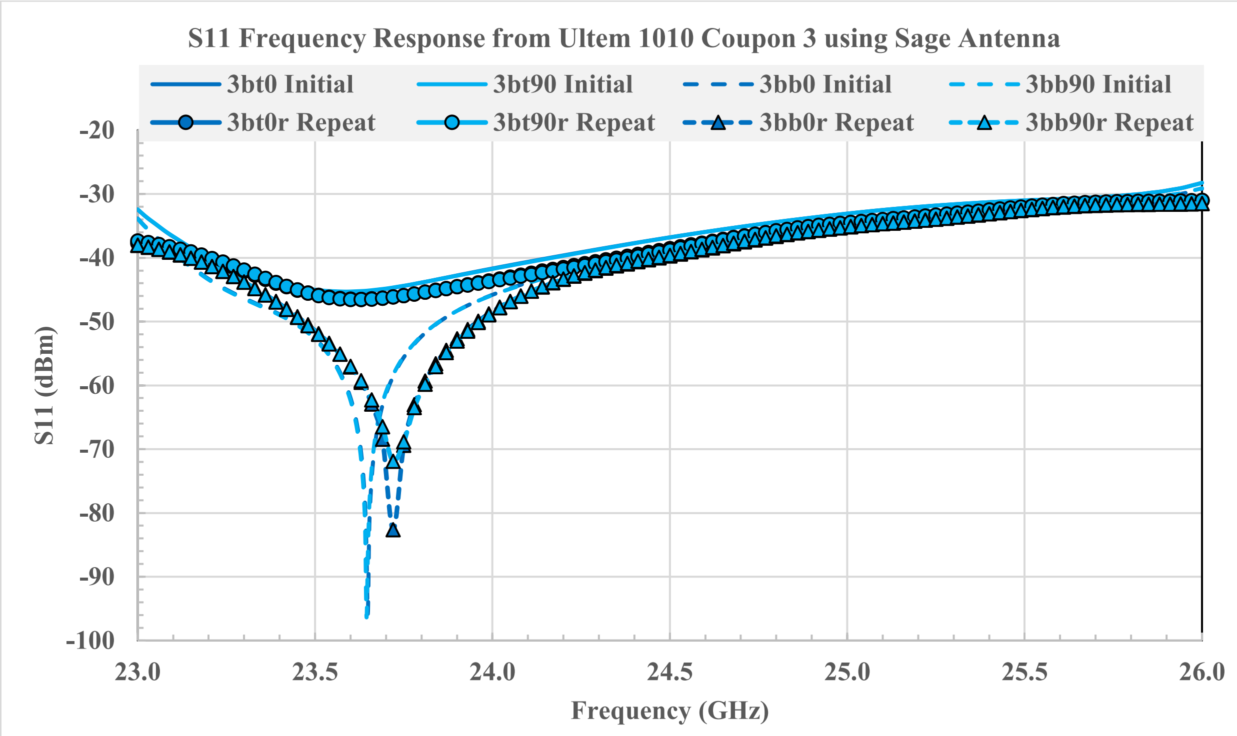

Figure 7. S11 Frequency Response of Ultem 9085 Coupon 3 after 8 months using Sage Antenna.

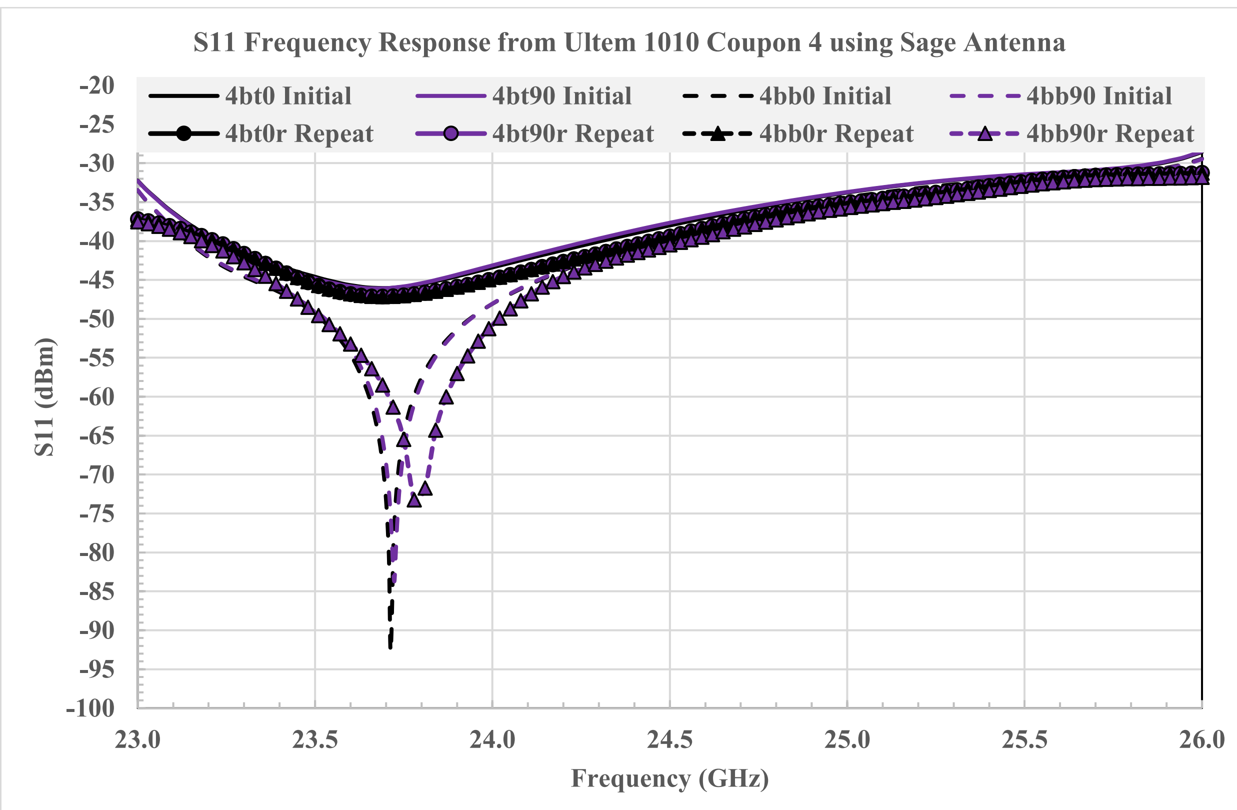

Figure 8. S11 Frequency Response of Ultem 9085 Coupon 4 after 8 months using Sage Antenna.

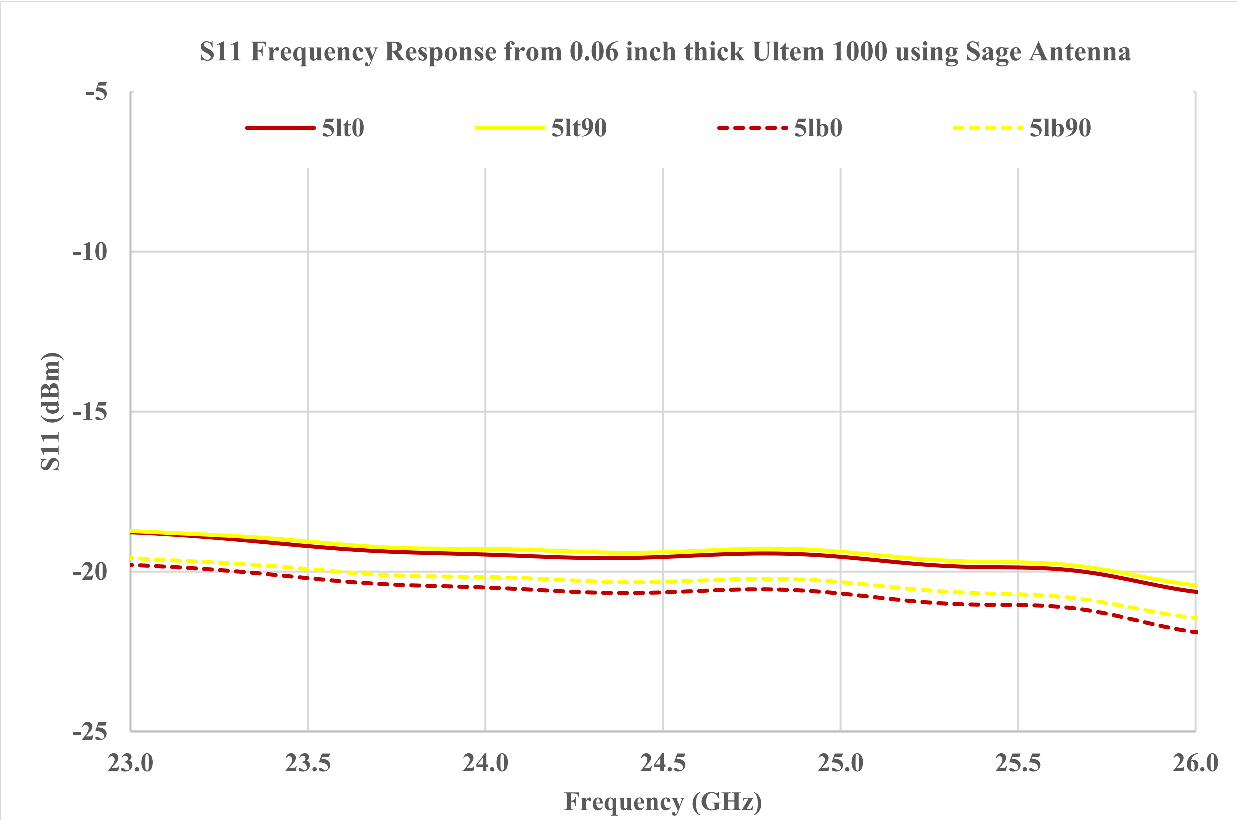

Figure 9. S11 Frequency Response of .06 inch thick Ultem 1000 Coupon 5 using Sage Antenna.

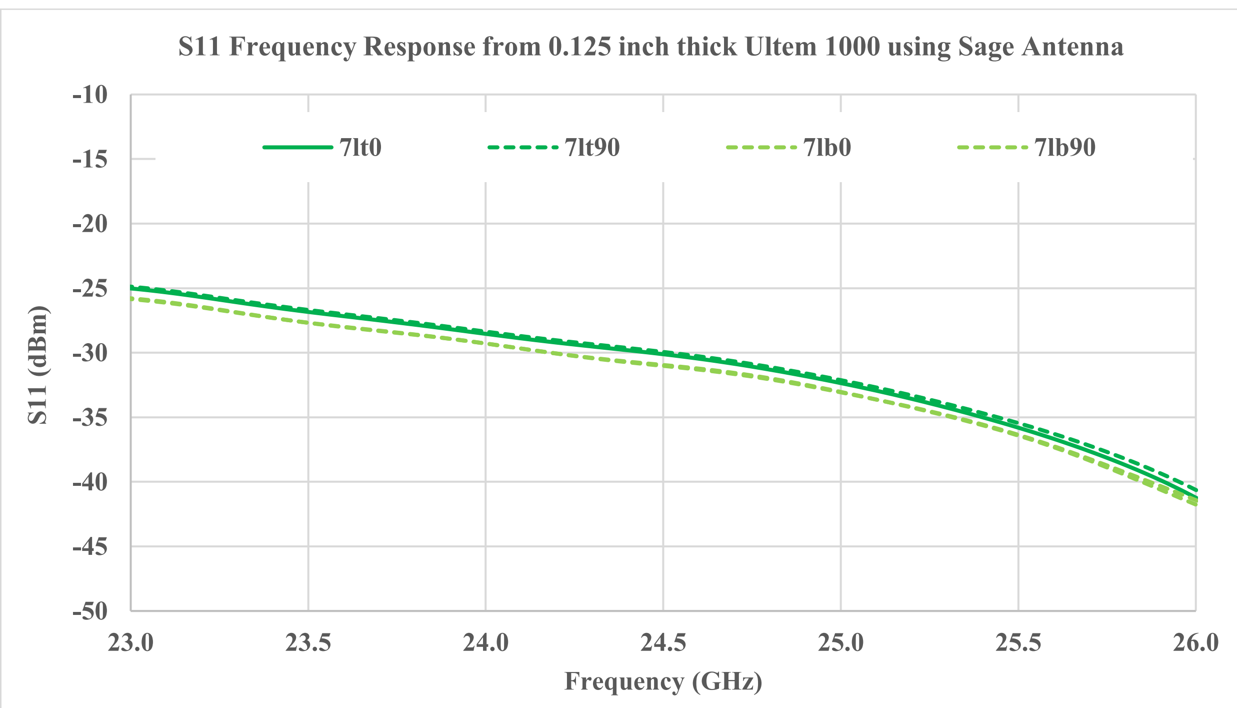

Figure 10. S11 Frequency Response of .125 inch thick Ultem 1000 Coupon 7 using Sage Antenna.

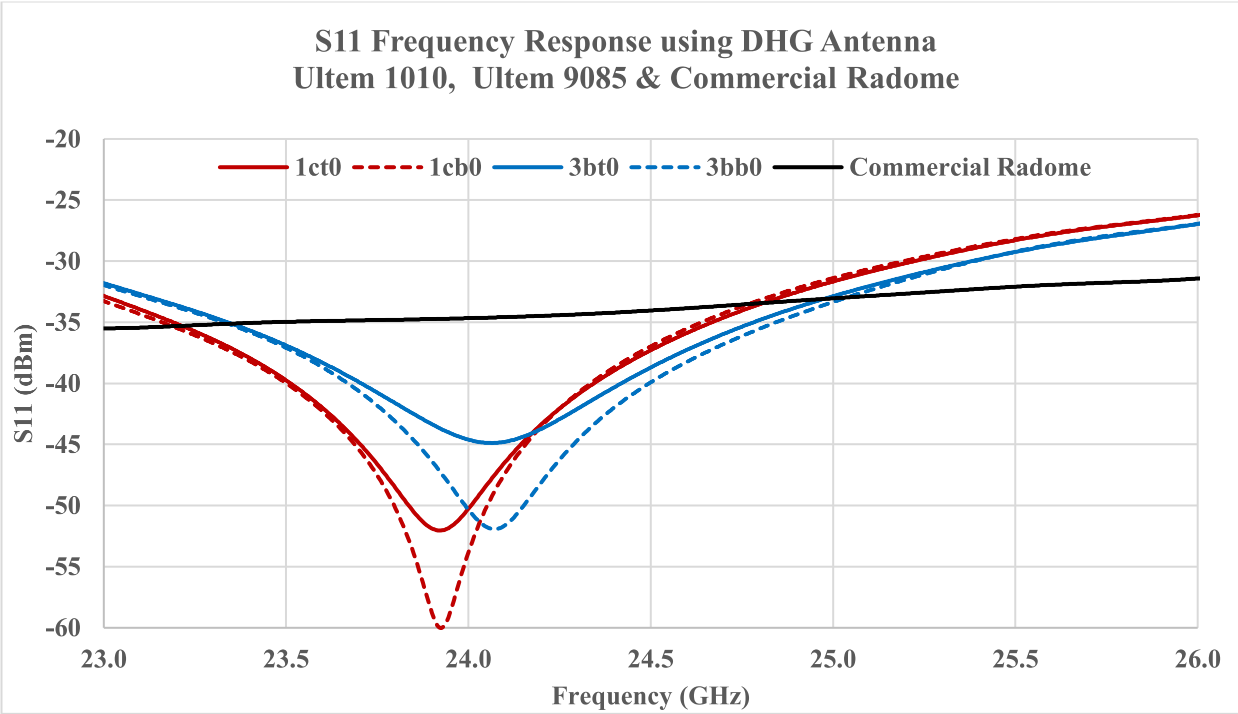

Figure 11. S11 Frequency Response of Ultem 1010, 9085 & Commercial Radome using DHG Antenna.

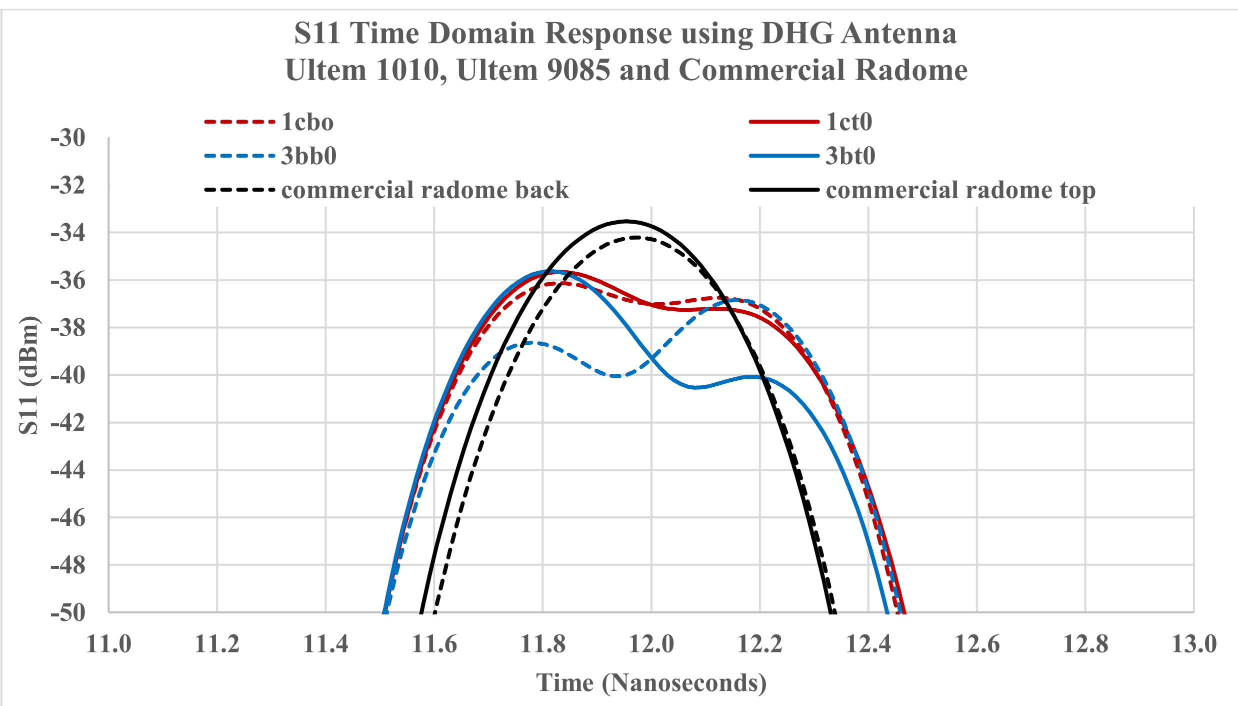

Figure 12. S11 Time Domain Response of Ultem 1010, 9085 & Commercial Radome using DHG Antenna.

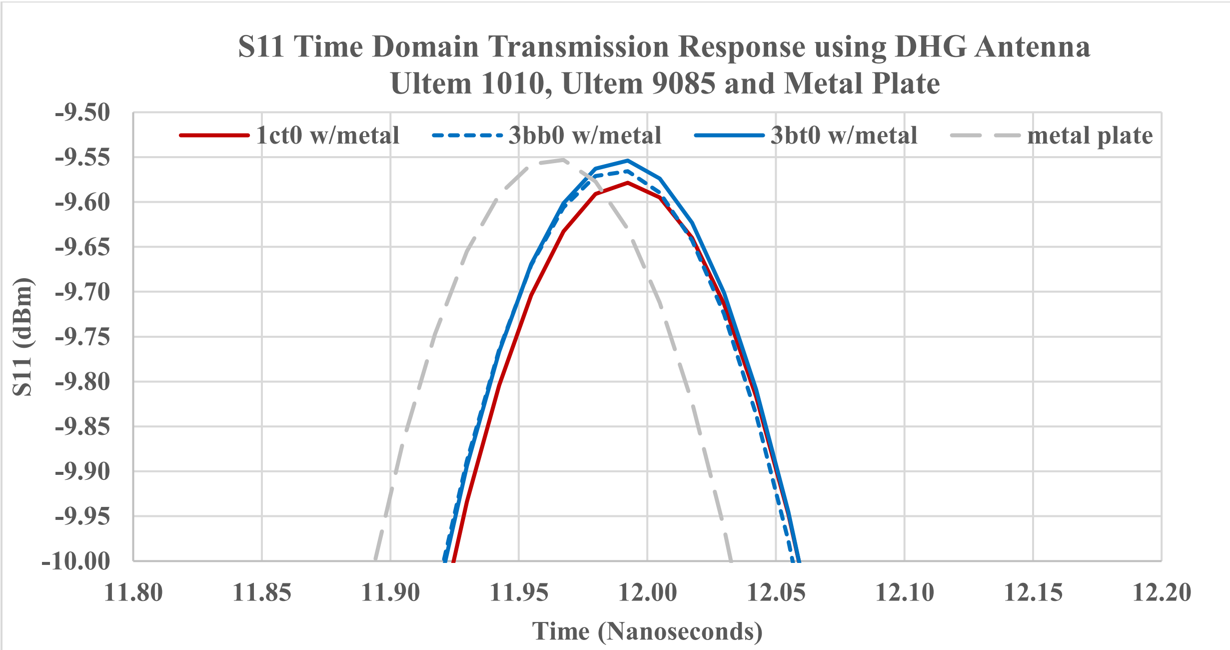

Figure 13. S11 Time Domain Transmission Response of Ultem 1010, 9085 & Metal Plate using DHG Antenna.

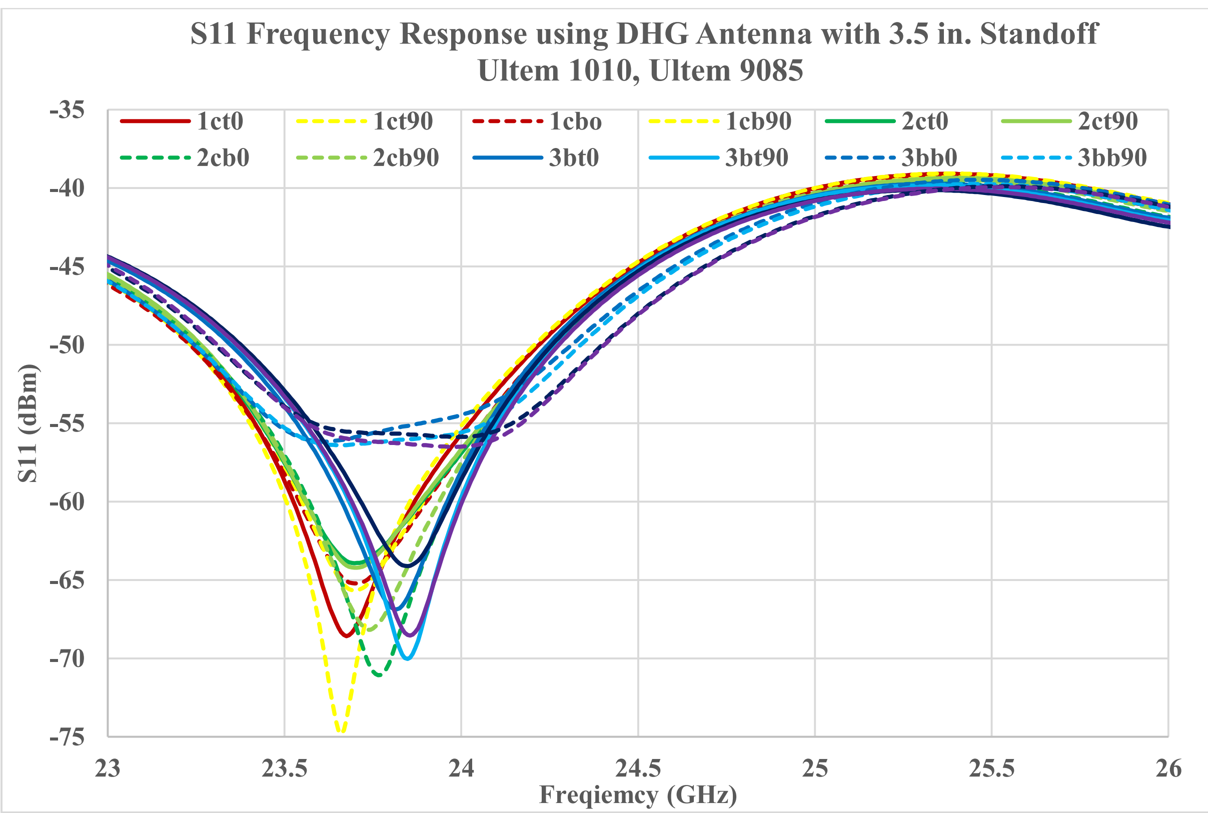

Figure 14. S11 Frequency Response of Ultem 1010 and Ultem 9085 using DHG Antenna with 3.5in standoff.

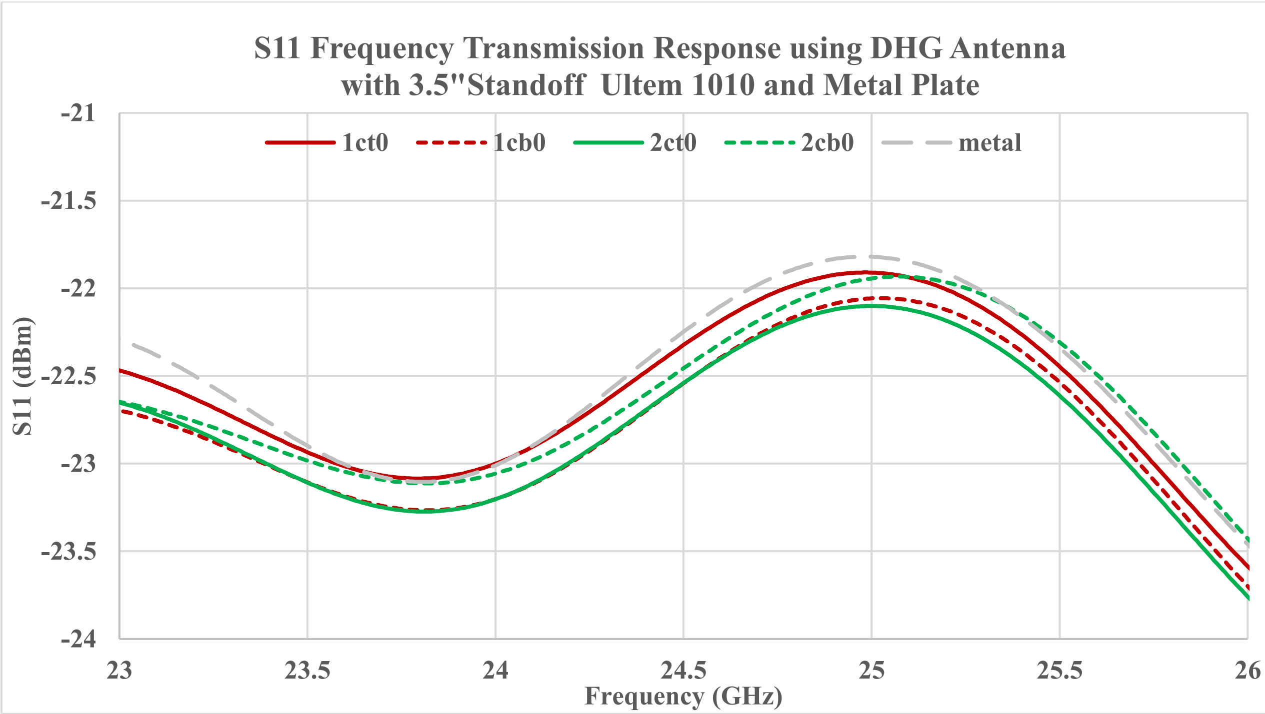

Figure 15. S11 Frequency Response of Ultem 1010 and Metal Plate using DHG Antenna with 3.5 in.

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14. ABSTRACT

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15. SUBJECT TERMS

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