

MANUFACTURABILITY and TRANSMISSIVITY of RADOMES FORMED with ALIGNED DISCONTINUOUS COMPOSITE REINFORCEMENT TAPE

Elizabeth Thompson
Pepin Associates, Inc.
P.O. Box 397
Greenville, ME 04441

ABSTRACT

Radomes come in a range of complex curved shapes and sizes, which may be difficult to form with standard continuous materials. Pepin Associates, Inc. has developed an aligned, discontinuous composite reinforcement material that stretches to form complex shapes without wrinkles or crimping. This material reduces time and labor costs associated with standard forming methods by eliminating the need to cut, dart, or otherwise manipulate the lay-up. The Pepin material can be manufactured with a wide range of fibers, including glass and quartz, which are the fibers of choice for radome applications. The work described in this paper examined the effects of fiber discontinuity in the Pepin material on the electrical properties of composites used to manufacture radomes. Comparative electrical testing was performed on both continuous and aligned discontinuous quartz/epoxy composite flat plates. Based on this testing, a demonstration radome was designed and fabricated.

1. INTRODUCTION

The most important design components of radomes are signal transmissivity and the ability to endure aerodynamically imposed stress and, in some cases, high aerokinetic heating loads during flight. To withstand these loads, complex conical shapes are employed to minimize the stresses of aerodynamic flow and environmental strike factors. As signal seeking air vehicles are advanced, radomes are exposed to more extreme load stresses and degradation of RF transmission signals. In order to accommodate such changes, materials that efficiently form a hemispherical shape are desirable. Pepin Associates, Inc. has developed an aligned, discontinuous composite reinforcement fabric that stretches to form complex shapes without wrinkles or crimping. The Pepin material can be manufactured with a wide range of fibers, including glass and quartz, which are the fibers of choice for radome applications.

Due to the architecture of the Pepin material, it is not known what effect the discontinuity will have on RF signal transmission. Flat laminates were created and tested for electrical property performance. The work described in this paper examines the effects of fiber discontinuity in the Pepin material on the electrical properties of composites used to manufacture radomes and is intended to reach radome designers and fabricators.

1.1 Related Work

As mentioned above, Pepin Associates, Inc. has developed a formable textile fabric, DiscoTex®, to allow fabrication of complex shaped advanced composite structures. The technology is now diversifying into an aligned, discontinuous, uni-directional tape format. This material is referred to as DiscoTape™ throughout the paper. PAI discontinuous materials can be made from various fibers; glass, quartz, carbon, ceramic, etc., making development of efficient designs more attainable.

1.1.1 DiscoTape™ Development

Pepin Associates, Inc. developed an aligned discontinuous prepreg tape (DiscoTape™) from continuous prepreg that will stretch easily to form complex shapes. DiscoTape™ is created by feeding a unidirectional tape through a die press. The continuous tape feeds through the die and roller and is cut into discrete lengths. Depending on the formability desired, the die can be quickly and easily changed to accommodate new patterns or cut lengths.

For the purposes of this work, we chose a brick-like pattern with 2.54 mm crosscuts perpendicular to the fiber direction. The distance between cuts along the fibers is approximately 5.08 cm. The die and the prepreg process diagram appear in Figure 1. below.

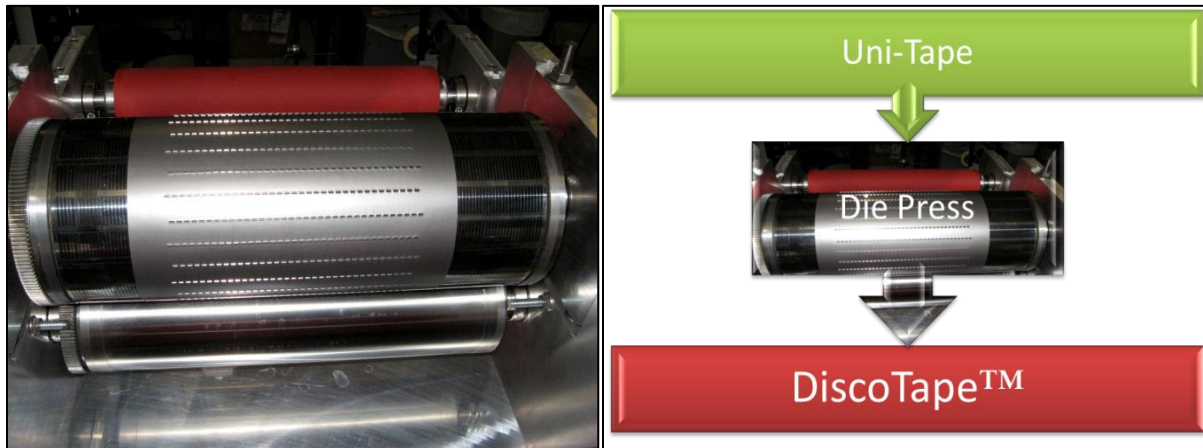


Figure 1. DiscoTape™ Machine and Process Diagram

1.2 Background on the Requirements

Due to their shape, radomes can be fairly difficult to make in production, suggesting that PAI aligned discontinuous materials may offer a solution. Radomes come in many different shapes and sizes, many of which are difficult to form with continuous composite reinforcement materials. It was not known what effect, if any, the discontinuity of the material would have on the transmissivity of a radar signal. No information could be found on discontinuous materials being used in the formation of radar and/or sonar protective structures. In order to learn how the discontinuity would affect the signal, PAI conducted electrical property testing with Radant Technologies.

Generally, PAI would use a woven fabric for dome shapes, but due to the simple nature of the transmissivity question, it was decided that testing the newly developed DiscoTape™ would yield the desired information.

2. EXPERIMENTATION

Based on research into common radome manufacturing materials, glass/epoxy prepreg was chosen for this work. To understand whether the discontinuous nature of the DiscoTape™ has an effect on transmissivity, a series of radio frequency tests were designed to compare PAI's discontinuous panels to continuous control panels.

As a first step, flat panels were characterized for core properties. From those results one could predict if the discontinuous material would behave differently from their continuous counterparts. Panel testing was conducted by Radant Technologies. Radant Technologies designs, evaluates and tests laminate radomes (electrically and structurally) for X-band to millimeter wave frequencies, routinely fabricating, testing, and evaluating flat panels as part of the process. All the laminates it uses are a mixture of a thermo-set resin (epoxy or cyanate ester) and fabric woven from either E-glass fiber or quartz fiber. The permittivity of these laminates is modeled by a mixture of resin and fiber that depends on their volume fractions, component permittivity, and shape.

2.1 Materials

Two types of aligned discontinuous glass/epoxy prepregs were tested against continuous control panels: S glass (Resin Content 35.5 ± 2.5 % Carbon black) and E glass (Resin Content 36 ± 1 %).

For each material above, 38.1 cm x 38.1 cm laminates were fabricated by PAI to allow testing at incidence angles up to 60° (which covers most practical microwave band applications). Panels included two 0.838 cm thick panels for X Band (~10 GHz) and two 0.198 cm thick panels for Q-Band (~ 45 GHz).

2.2 Measurement Approach

There are several approaches typically employed to measure radome performance. While the details of the mechanical positioning system can be very different for each approach, a basic test system includes a control computer, transmit signal source, source positioner, radome positioner, position control equipment, test antenna, RF signal multiplexer and the receiver. Described below are typical parameters measured to characterize the performance of a radome.

2.3 Test Definitions

Brief descriptions of the electrical performance tests are described in the following sections.

2.3.1 Transmission Efficiency (TE)

Transmission Efficiency is the percentage of microwave energy that passes through a radome, typically measured over various angular regions (which usually represent the area of the radome actually used by the radar system). It is measured by comparing power levels received

by a test antenna in two different conditions. A reference measurement is made with the radome off, then again after installation of the radome over the radar antenna. The resulting data is plotted over the surface of the radome. While ideally transparent, all radomes will have losses as the RF signal passes through it due to a combination of reflections, diffraction, absorption, refraction and depolarization. [Darling]

2.3.2 Insertion Phase Delay (IPD)

This is a measure of how much additional phase delay is accumulated by a plane wave passing through the test panel relative to the same wave traveling in free space. Phase distortion directly leads to BD/BS and Pattern distortion. IPD is measured simultaneously with TE.

2.3.3 Reflectivity (RF)

Reflectivity is the change in the magnitude of the reflection coefficient at the port of the radar antenna which is caused by the presence of the radome. This is measured using a reflectometer with a remote head. The reflection coefficient is measured before and after the radome is installed with the antenna pointing out into a reflection-less environment (such as an anechoic chamber or an outdoor range). Ideally, this measurement is independent of pointing direction of the radar antenna. [Darling]

2.3.4 Depolarization & Scattering of Signal

This employs the same basic setup as TE and IPD but is done independently. For the tests above, we transmit at one polarization and receive at the same polarization (this is called co-pol). For depolarization testing, we transmit at one polarization and we receive in the orthogonal polarization. Ideally, we should receive very little energy in this cross-pol channel. This test quantifies how much energy is depolarized (scattered into the cross-pol channel) as the wave passes through the test panel. We want to know if the discontinuity of the fibers is causing scattering and de-polarization of the signal. This will depend on the frequency of the signal and the fiber architecture.

2.3.5 Dielectric Constant (DC) and Loss Tangent (LT)

These tests will measure the relative dielectric constant and loss tangent of the panel material. Data is obtained during TE and IPD testing. Testing the material at microwave frequencies can be used in comparison with other candidate radome materials.

2.4 Test Panel Fabrication

Eight test panels (38.1 cm x 38.1 cm) were fabricated by PAI to allow testing at incidence angles up to 60 degrees (which covers most practical microwave band applications). Panels of different thicknesses that are tuned to different frequency bands were also fabricated. These included: 4 panels of approximately 0.838 cm thickness for X Band (~10 GHz) and 4 panels of approximately 0.198 cm thickness for Q Band (~ 45 GHz). Half of the panels were control (continuous) panels and half were discontinuous.

2.5 Procedure

Radant Technologies conducted the Radio Frequency (RF) testing at their facility in Stow, Massachusetts. The test matrix is shown below followed by brief test details.

Table 1. Test Matrix for PAI Panels

ELECTRICAL PROPERTIES OF DISCOTAPE™			
RF Test	Material	Type	Layup
TE Transmission Efficiency	Unidirectional Glass Epoxy	<i>Discontinuous S glass</i>	DiscoTape™ [0/90] ₇ <i>0.078in. thick</i>
IPD Insertion Phase Delay			DiscoTape™ [0/90] ₃₀ <i>0.33in. Thick</i>
Reflectivity		<i>Continuous S glass</i>	CONTROL [0/90] ₇ <i>0.078in. thick</i>
			CONTROL [0/90] ₃₀ <i>0.33in. Thick</i>
Depolarization & Scattering of Signal		<i>Discontinuous E glass</i>	DiscoTape™ [0/90/0/90/0/90/0] <i>0.078in. thick</i>
DC Dielectric Constant			DiscoTape™ [0/90] ₁₆ <i>0.33in. Thick</i>
LT Loss Tangent		<i>Continuous E glass</i>	CONTROL [0/90/0/90/0/90/0] <i>0.078in. Thick</i>
			CONTROL [0/90] ₁₆ <i>0.33in. Thick</i>

Transmission Efficiency (TE) and Insertion Phase Delay (IPD) were measured at 0°, 30°, and 60° Vertical Polarization (H-Plane) and Horizontal Polarization (E-plane) at four panel locations for each test angle for increased accuracy. Reflectivity will be measured at 0° and 30° E and H plane incidence angles. Dielectric Constant and Loss Tangent will be measured at multiple positions for increased accuracy. Depolarization will be measured at 0° and 30° E plane and H plane incidence angles.



Figure 2. Testing Station at Radant Technologies



Figure 3. E glass panel placed in test assembly.

2.5.1.1 Control Panels

Control panels were fabricated with 0.838 cm thick stack of unidirectional tape provided by Northern Composites. The unitape was cut into 38.1 cm square pieces and layed up into the

desired thicknesses. These included: 2 panels of approximately 0.838 cm thickness for X Band (~10 GHz) and 2 panels of approximately 0.198 cm thickness for Q Band (~ 45 GHz).

2.5.1.2 DiscoTape Panels

The DiscoTape plies were processed with the flex die to create small cuts perpendicular to the fiber direction at about 3.3 cm increments for the S glass and 5.08 cm increments for the E glass.

All panels (continuous and discontinuous) were stacked [0/90] to minimize brittleness in the lateral direction and to mimic a layup we might use when forming a dome or other complex shape.

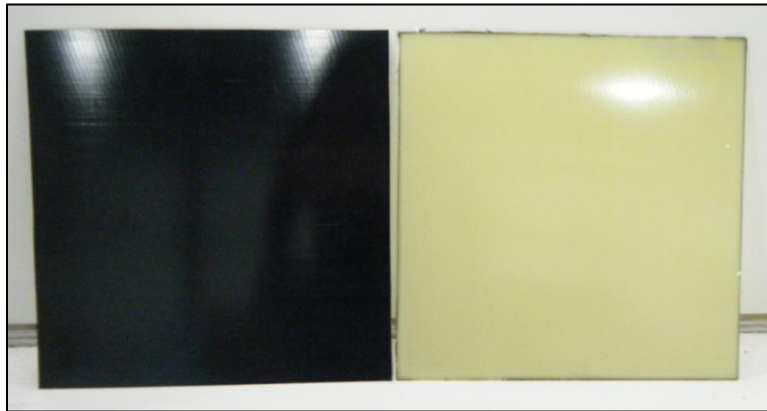


Figure 4. S glass (left) and E glass (right) Test Panels

2.6 Variables

There are numerous applications operating at the various frequency bands. X Band is a common band for both Radar and communications. Many radomes need to operate at 2 or 3 bands including X and Q. The S glass originally employed the 3.3 cm cuts as a result of the technology transfer from DiscoTex® fabric to DiscoTape™. The 3.3 cm length allows the material to conform over a broad range of contours.

3. RESULTS

Overall, the RF testing shows that discontinuous materials can be used in electrical applications. All charts below show a horizontal reference line (REF) along the top of the curve. The REF line represents the testing facilities calibration measurement without a panel present. Any deviation from the REF line is a result of insertion loss created by a PAI Panel. After initial RF testing, it was discovered that the 3.3 cm segment length was causing the resonance seen at the X Band (at around 9 GHz where the free space wavelength is 3.3 cm).

The curves are showing how much power passes thru the PAI Panel versus frequency.

Figure 5. below shows that resonance may be tuned to certain frequencies depending on the length of the cut segments. Resonance location may be varied by changing the distance

between cut increments on the tape. A 3.3 cm cut increment produces a resonance at approximately 9 GHz that is evident by the increased insertion loss. Changing the cut increment to 5.08 cm moves the resonance to approximately 6 GHz so that the Control and Disco panels are electrically identical at X Band, as well as frequencies away from this resonance. In doing so, one would have to assess if the material still possessed the properties required for forming the desired shape. Tighter radius layups will require the increments to be shortened, while larger, gentle curves may do well with longer increments.

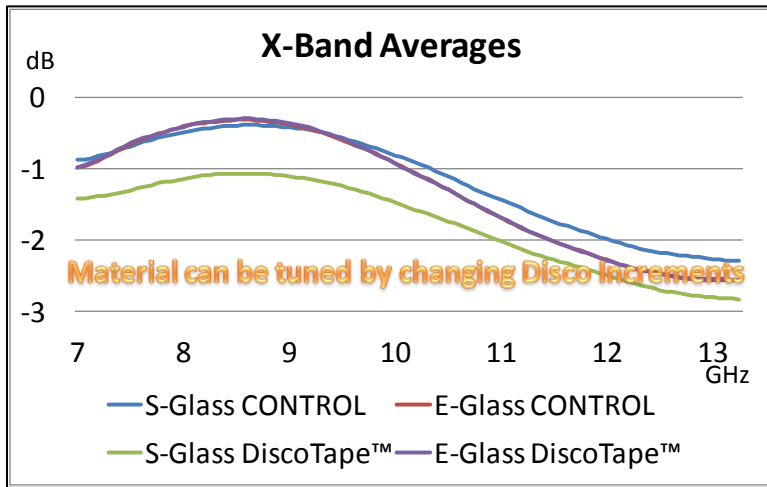


Figure 5. Comparison of S glass and E glass results at 3.08 cm and 5.08 cm cut increments, respectively.

3.1 S glass RF Testing

Initial data showed that the PAI Panels performed well with the exception of the discontinuous panels being prone to a higher level of signal loss at the X Band frequency. The discontinuity occurred at 3.83 cm increments in these panels. At Q Band, the discontinuous panel performed as well as the control panel with no detectable impact on RF performance.

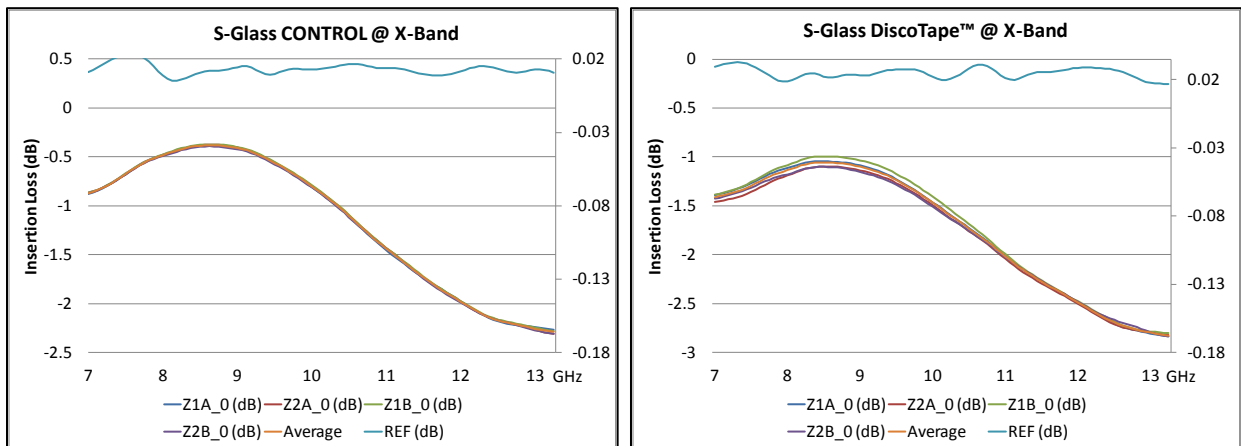


Figure 6. Comparison of S glass Electrical Performance at X Band Frequencies

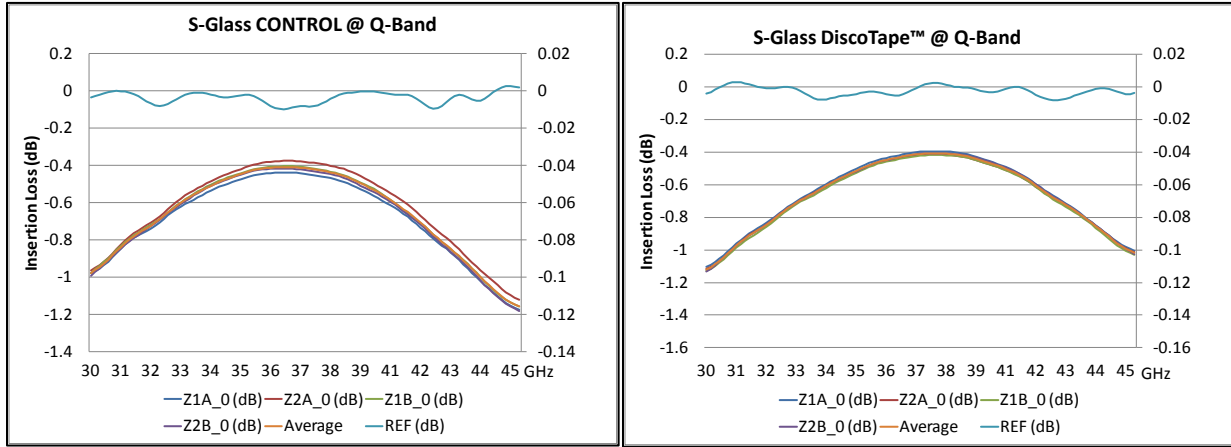


Figure 7. Comparison of S glass Electrical Performance at Q Band Frequencies

After considering probable causes of X Band signal loss, it was hypothesized that the discontinuity increment was causing resonance around 9GHz, where the free space wavelength is the same as the cut increments; 3.3 cm. The testing facility (Radant Technologies) suggested a simple solution: Change the cut increment, dependent on the application frequency of interest, in order to move the resonance out of the band of interest. For example, it is expected that changing the spacing to 5.08 cm would to shift the resonance to 5.9 GHz, which would not interfere with the large majority of radome applications.

In addition to changing the cut increments, it was suggested that E glass is typically lower loss than the S glass used. The S glass employed contained 2.5 % carbon black by weight, which would also contribute to signal loss. PAI decided to conduct a second round of testing on higher performing materials. E glass was chosen without carbon coloring and the cut spacing was increased from 3.3 cm to 5.08 cm for the next tests.

Tables 1 and 2 express Dielectric Constant (E_r) and Loss Tangent ($\tan\delta$) at both X and Q band frequencies. The permittivity of a lossless material is equal to $E_r E_0$ where E_r is the relative dielectric constant; relative to free space (vacuum) and is unitless, and E_0 is the permittivity of free space (a fixed constant).

$\tan\delta$ is Tangent (δ) and is also unitless. A material is lossy if it has a non-zero $\tan\delta$ and its permittivity (E) then becomes complex and can be expressed as:

$$E = E' - jE'' = E_r E_0 (1 - j \tan\delta) \quad [1]$$

where $\tan\delta = E''/E'$ (i.e., the ratio between imaginary and real parts of the permittivity).

Dielectric Constant is 1.0 for vacuum. From an electrical perspective, materials with E_r as close to 1 as possible are ideal. However, materials close to 1 (low density foam for example) may not be suitable for many structural or radome applications. Practical, low speed, low temp, radome applications might employ materials with E_r in the 3 - 4.5 range. High speed missile radomes often use ceramic based materials with E_r over 5.5. There is often a trade-off between mechanical and electrical properties. Over designing for strength will generally

degrade electrical performance, while optimizing electrical properties may compromise strength. Pepin Associates discontinuous materials fall in the practical range mentioned above.

Loss Tangent ($\tan\delta$) is expressed as a percentage, where 100 % (or 1.0) is perfectly lossless and 0 % (or 0.0) is perfectly lossy. $\tan\delta$ should be as small as possible as this is what drives intrinsic insertion loss of the material. Insertion loss, in this case, is the loss of signal power resulting from the insertion of a device (PAI Panel) between the transmitter and receiver. Figure 4. above shows a PAI E glass panel test set-up, illustrating how the signal is transmitted through the panel.

Table 2. S Glass Permittivity Evaluation Summary at 0° Incidence

X Band (8 to 12 GHz)				
<i>Panel</i>	<i>Thickness (mils)</i>	<i>Plane</i>	<i>Dielectric Constant</i>	<i>Loss Tangent</i>
Control	336	H	4.05	0.021
Control	336	E	4.05	0.020
DiscoTape™ 1	333	H	3.91	0.066
DiscoTape™ 1	333	E	3.92	0.059
Q Band (33 to 50 GHz)				
<i>Panel</i>	<i>Thickness (mils)</i>	<i>Plane</i>	<i>Dielectric Constant</i>	<i>Loss Tangent</i>
Control	80.3	H	3.85	0.025
Control	80.3	E	3.84	0.026
DiscoTape™ 2	77.6	H	3.91	0.025
DiscoTape™ 2	77.6	E	3.91	0.026

Table 3. E Glass Permittivity Evaluation Summary at 0° Incidence

X Band (8 to 12 GHz)			
<i>Panel</i>	<i>Thickness (mils)</i>	<i>Dielectric Constant</i>	<i>Loss Tangent</i>
Control	327	4.444	0.0180
DiscoTape™	327	4.435	0.0176
Q Band (33 to 50 GHz)			
<i>Panel</i>	<i>Thickness (mils)</i>	<i>Dielectric Constant</i>	<i>Loss Tangent</i>
Control	71	4.48	0.0223
DiscoTape™	69.5	4.56	0.0206

3.2 E glass RF Testing

As expected, the E glass panels performed better than the S glass panels with carbon black. The tests show lower loss than the S glass and resonance no longer appeared at the X Band frequency. No difference was seen between the discontinuous and control panels at either X or Q Band, confirming that the resonance was moved out of the way of the signal by increasing the length of the cut increment to 5.08 cm.

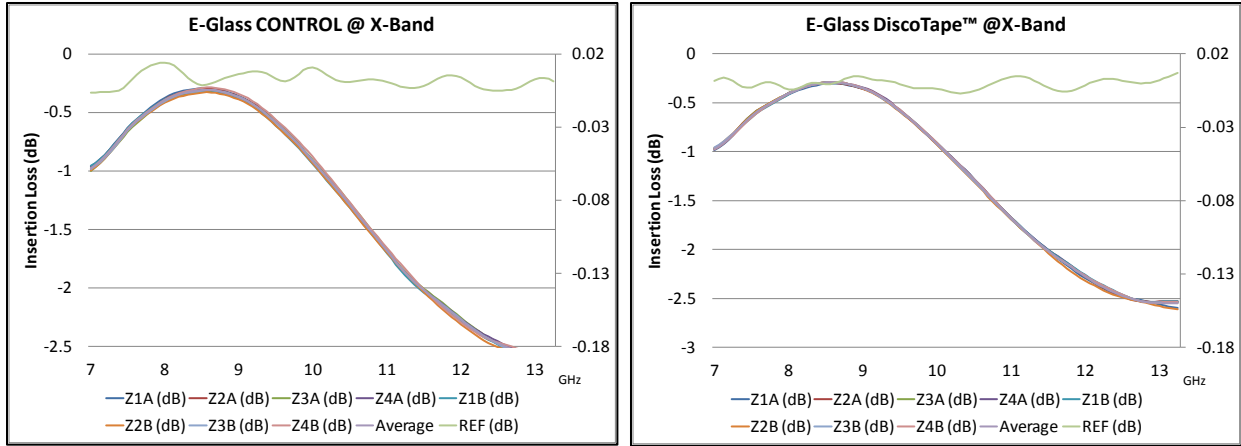


Figure 8. Comparison of E glass Electrical Performance at X Band Frequencies

Figures 9 and 10. below show that the discontinuous E glass performs as well as the continuous in the Q Band frequency.

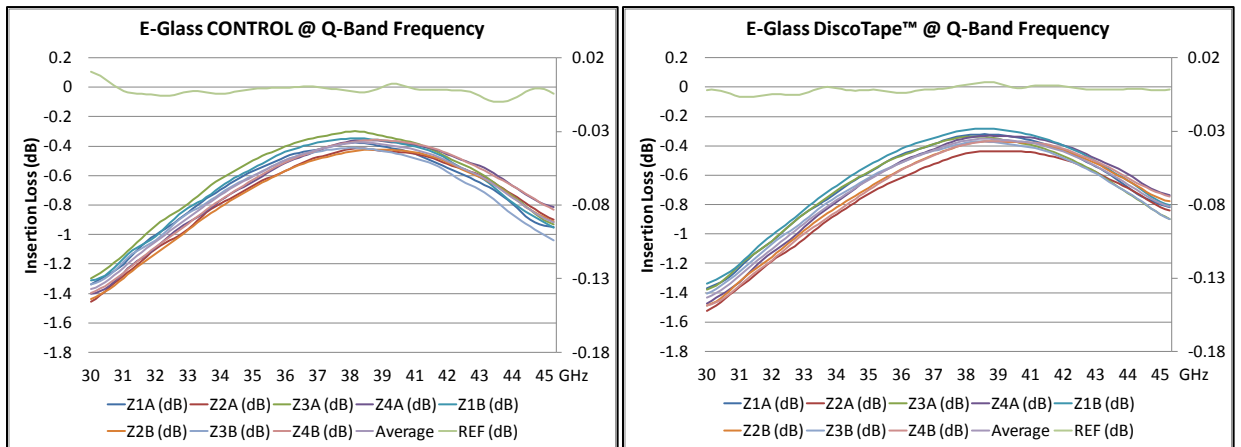


Figure 9. Comparison of Continuous and Discontinuous E glass at Q Band Frequency

To better see the relationship of E glass panels at the Q Band frequency, the averages of the curves were compared on the chart shown in Figure 10 below. Note that the two peaks of the curves are not at the same frequency location due to the slight difference in thickness of the two panels. This is normalized out when calculating Dielectric Constant and Loss Tangent.

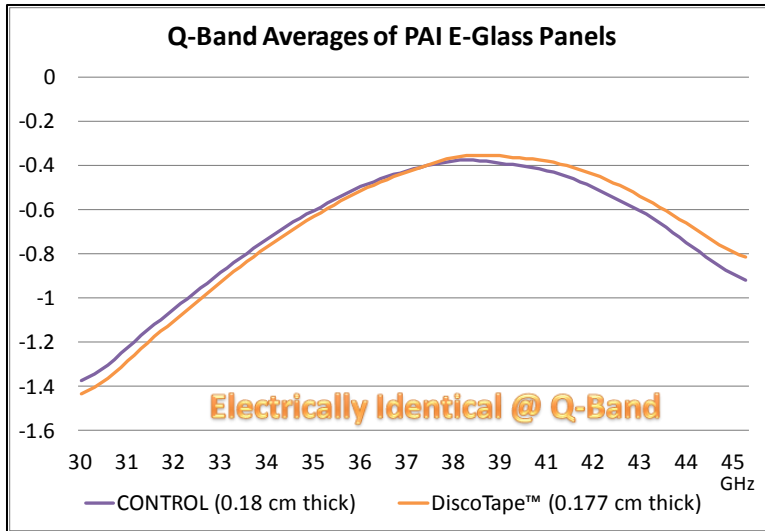


Figure 10. E Glass Panels Show Electrically Identical Performance at the Q Band Frequency.

4. CONCLUSIONS

Pepin Associates, Inc. has shown that discontinuity does not always affect transmissivity of a radar signal. Overall, the losses were about 10 % lower for the E glass panels versus the S glass panels. There are several factors affecting the signal loss or degradation, all of which may be altered accordingly.

- E glass is typically lower loss than the S glass employed in the initial round of RF tests.
- Carbon should not be used in radar applications as it is conductive, resulting in degradation of the signal.
- Resonance may be varied or eliminated by changing the distance between cut increments on the tape. In doing so, one would have to assess if the material still possessed the properties required for forming the desired shape. Tighter radius layups will require the increments to be shortened, while larger, gentle curves may do well with longer increments.
- Choice of matrix chemistry may lead to improved performance. In addition to epoxies, other resins may be suitable. Cyanate ester generally has a lower loss tangent, leading to lower insertion loss.

Pepin Associates, Inc. aligned discontinuous materials may now be considered when designing for radar applications requiring complex shapes AND low loss materials.

5. ACKNOWLEDGEMENTS

Pepin Associates, Inc. would like to acknowledge the Office of Naval Research for funding the work described in this paper. We would also like to thank John Maciel at Radant Technologies for performing the electrical property testing and explicating the results.

6. REFERENCES

6.1 Web Sites

Darling, Thomas B. "Military Radome Performance and Verification Testing," *www.mi-technologies.com*. September 15, 2008. MI Technologies, Suwanee, GA. Accessed January 10, 2012 <[http:// www.mi-technologies.com/literature/literature.htm#Technical Papers](http://www.mi-technologies.com/literature/literature.htm#Technical%20Papers) ">