



Refractive Index of Polyaryletherketone (PEEK) at X- and W-Band

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Summary

This report details refractive index measurements of polyaryletherketone (PEEK) thermoplastic between X-band (8 to 12 GHz) and W-band (75 to 110 GHz) frequencies. Scattering-parameter data are collected using both traditional waveguide and modified free-space techniques. The complex-valued refractive index is calculated using the standard Nicolson-Ross-Weir method. Results indicate that PEEK's refractive index is $n = 1.783 - 0.001i$ across X-band and $n = 1.792 - 0.007i$ across W-band. Therefore, PEEK exhibits a moderate real refractive index component and low transmission loss. Coupled with its favorable mechanical and thermal properties, this makes PEEK an ideal material to inspect using NASA's submillimeter radiofrequency-based technology.

1.0 Introduction and Motivation

NASA is developing submillimeter radiofrequency- (RF-) based nondestructive evaluation (NDE) techniques (Refs. 1 to 3) to assist in the design, manufacture, and certification of nonmetallic aerospace components. Example components include ceramic thermal and environmental barrier coatings (Ref. 4) and polymer-based structural components. The objective is to design safer components, decrease their manufacturing costs, and reduce time-to-certification (Ref. 5). Doing so enhances NASA's exploration capabilities and strengthens both national air and space commercial markets.

Polyaryletherketone (PEEK) is a high-value thermoplastic routinely used in aerospace applications for its low mass and good mechanical and thermal properties (Ref. 6). PEEK is versatile, capable of being produced in pure polymer form, in a composite with carbon fiber, or even additively manufactured. PEEK has been in production since the late 1970s (Ref. 7), but has recently seen increased use because of the aerospace industry's consistent push for lighter weight vehicles and reduced emissions (Ref. 8). Therefore, PEEK component design, manufacturing, and certification could benefit from NASA NDE technology.

PEEK's electrical properties, especially at submillimeter RF wavelengths, are not well documented. For example, there does not appear to be any current documentation for PEEK RF properties at W-band frequencies (75 to 110 GHz). There are some references available taken at either lower (2.45 GHz) frequencies (Refs. 9 and 10), higher terahertz frequencies (Ref. 11), or as blended PEEK mixtures (Ref. 12). The lack of specific W-band data, coupled with the few references at other frequencies, means that a targeted investigation must be conducted in order to determine if PEEK is indeed a good candidate material for NASA RF-based NDE inspection. This report presents the complex refractive index of PEEK 450G unfilled polymer (Ref. 6) across X- and W-band frequencies, measured in both a waveguide and free-space configurations.

2.0 Determining a Material's Complex Refractive Index Using S-Parameters

Vector network analyzers (VNAs) (Ref. 13) are routinely used to measure complex-valued scattering parameters (S-parameters) of electrical circuits. S-parameters provide a useful means to determine the complex refractive index of materials over a wide frequency range, by measuring the magnitude and phase of reflected and transmitted components of an electric field incident on the material. S-parameters are collected using several different measurement methods including waveguide, free space, and cavity resonators (Ref. 14). Regardless of the experiment technique, an extraction algorithm is required to retrieve the complex refractive index from a measured S-parameter set (Ref. 15). Although several extraction algorithms exist, the Nicolson-Ross-Weir (NRW) algorithm and its variants have become the standard (Refs. 16 to 18). The generalized NRW algorithm is outlined below.

The first step is to determine the propagation factor,

$$\gamma_0 = \sqrt{k_c^2 - k_0^2} \quad (1)$$

where k_c^2 is the cutoff wavenumber of the system and k_0^2 is the free-space wavenumber. Note for free-space measurements $k_c = 0$. Next, the transmission term, in this case S_{21} , must be phase adjusted to account for material thickness such that

$$S_{21} = S_{21} e^{-\gamma_0 \cdot d} \quad (2)$$

where d is the physical material thickness. An intermediate term X is then calculated:

$$X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \quad (3)$$

The reflection coefficient R is calculated using

$$R = X \pm \sqrt{X^2 - 1} \quad (4)$$

where the appropriate root selection is made by requiring $|R| < 1$. The transmission coefficient T is then

$$T = \frac{S_{11} + S_{21} - R}{1 - R(S_{11} + S_{21})} \quad (5)$$

A second intermediary term Λ is required such that

$$\frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi d} \ln\left(\frac{1}{T}\right) \right]^2 \quad (6)$$

Because T is complex, there are an infinite number of solutions to Equation (6). This may be shown explicitly by rewriting the equation as

$$\ln\left(\frac{1}{T}\right) = \ln\left(\frac{1}{|T|}\right) + i(\text{Arg}\{T\} + 2\pi m) \quad (7)$$

where m is an integer and $\text{Arg}\{T\}$ is the unwrapped phase of T . The correct value for m can be automatically determined by comparing the measured and calculated group delays. For this extra step the reader is referred to References 16 and 17.

Now, the relative permeability μ_r is calculated using

$$\mu_r = \frac{1 + R}{(1 - R)\Lambda \sqrt{\left(\frac{1}{\lambda_0^2}\right) - \left(\frac{1}{\lambda_c^2}\right)}} \quad (8)$$

recalling that free-space wavelength is $\lambda_0 = 2\pi \cdot k^{-1}$, and the cutoff wavelength of the measurement system is λ_c . The relative permittivity ϵ_r is then

$$\epsilon_r = \frac{\lambda_0^2}{\mu_r \left[\left(\frac{1}{\lambda_c^2}\right) - \left(\frac{1}{\Lambda^2}\right) \right]} \quad (9)$$

Finally, the refractive index is

$$n = \sqrt{\epsilon_r \cdot \mu_r} \quad (10)$$

If the material under test is known to be nonmagnetic, this implementation of the NRW algorithm may be simplified by forcing $\mu_r = 1 + 0i$.

Section 3.0 details the experimental apparatuses used to collect S-parameter data from PEEK 450G polymer and presents the resulting complex-valued refractive index calculated using the NRW algorithm outlined in this section.

3.0 Experimental Setup and Results

NASA's new NDE technology utilizes focused, free-space RF beams operating across W-band frequencies (75 to 110 GHz) to interrogate nonmetallic aerospace vehicle components. Refractive index measurements at high frequencies and in free space are difficult, and therefore the refractive index of PEEK 450G was first measured across X-band frequencies (8 to 12 GHz) using a traditional waveguide approach. This provides a validation point to compare W-band measurements against.

3.1 X-Band Waveguide Measurements

The X-band measurement setup consists of a VNA attached to two sections of WR-90 waveguide (Figure 1). A small sample holder is placed between the WR-90 waveguides during testing. The VNA is stepped across the band in 8.5-MHz increments with enough measurements at each frequency to utilize a 30-Hz-wide digital filter on the receiver intermediate frequency. These settings help ensure that stable and reliable S-parameter data are recorded.

Before collecting data, the VNA is calibrated using a standard thru-reflect-line (TRL) procedure (Refs. 19 and 20). TRL calibrations consist of collecting S-parameters from the experimental hardware in three configurations. First, the two WR-90 waveguides are connected without the sample holder present, constituting the "thru" measurement. A reflector plate is then placed between both ends of the WR-90 waveguide, producing the "reflect" data. Finally, a known length of empty waveguide is installed between the waveguide sections, resulting in the "line" calibration dataset. In addition to calibration, software time gating is used to minimize hardware characteristics remaining in the measured data. A time gate span of 2.0 ns was used in this experiment.

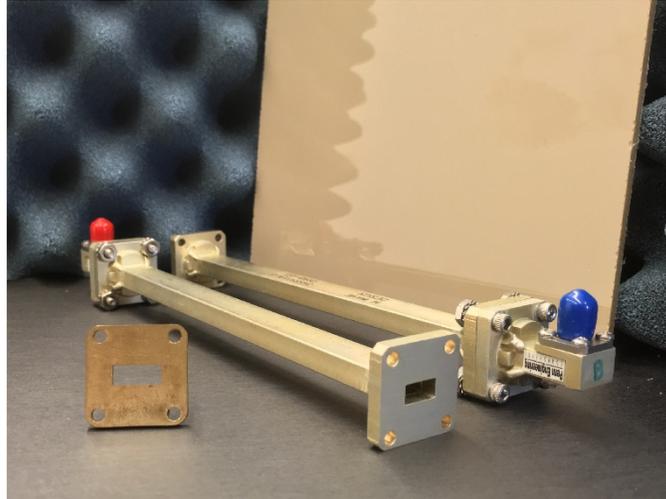


Figure 1.—Waveguides (center) and sample holder (left) used to measure scattering parameters of PEEK 450G (back right). Both waveguide sections are attached to a vector network analyzer using radiofrequency coaxial cables.

It is now possible to collect material property data from the experimental setup. PEEK 450G samples were cut and polished to final test dimensions of 22.86 by 10.16 by 3.2 mm. Samples were inserted into the waveguide, and the resulting S-parameters were recorded on the VNA. Figure 2 displays the resulting complex refractive index values calculated using the NRW algorithm detailed in Section 2.0. It is clear from the figure that the real component of the refractive index is stable across the frequency range, and the small imaginary component indicates minimal transmission loss. The average refractive index across the X-band is $n = 1.783 - 0.001i$.

3.2 W-Band Free-Space Measurements

Now that benchmark RF properties are established at the X-band, the refractive index of PEEK 450G may be determined across the W-band. The experimental setup for this task is similar to that used by NASA’s submillimeter RF NDE inspection technology. Unlike the X-band system, which used a waveguide to propagate RF waves through the material, the W-band system operates in free space.

The experimental setup (Figure 3) consists of a VNA attached to two W-band horn antennae, which propagate RF waves through a pair of polytetrafluoroethylene (PTFE) lenses. Each lens pair focuses the antenna beam onto the center of the sample, with a spot size of approximately 10 mm. RF-absorbing material is used to create a 15-mm-diameter aperture around the point of intersection between the RF beam and sample to reduce any diffraction effects from the sample edges.

High-frequency measurement systems are sensitive to submillimeter displacements of the antennae, optical components, and sample. Therefore TRL calibration, which requires a “line” measurement, is not ideal. A suitable alternative is thru-reflect-match, or TRM, calibration (Refs. 21 and 22). Like TRL, TRM calibration requires S-parameter data “thru” the system, without a sample present. Likewise, “reflect” data, captured from a reflecting metallic plate placed in the sample location, are also required. However, TRM uses RF-absorbing material placed on either side of the sample location to acquire “match” data, replacing the TRL’s “line” dataset. After TRM calibration is complete, a 400-ps time gate is applied to the S-parameter data to minimize multiple reflection interference effects.

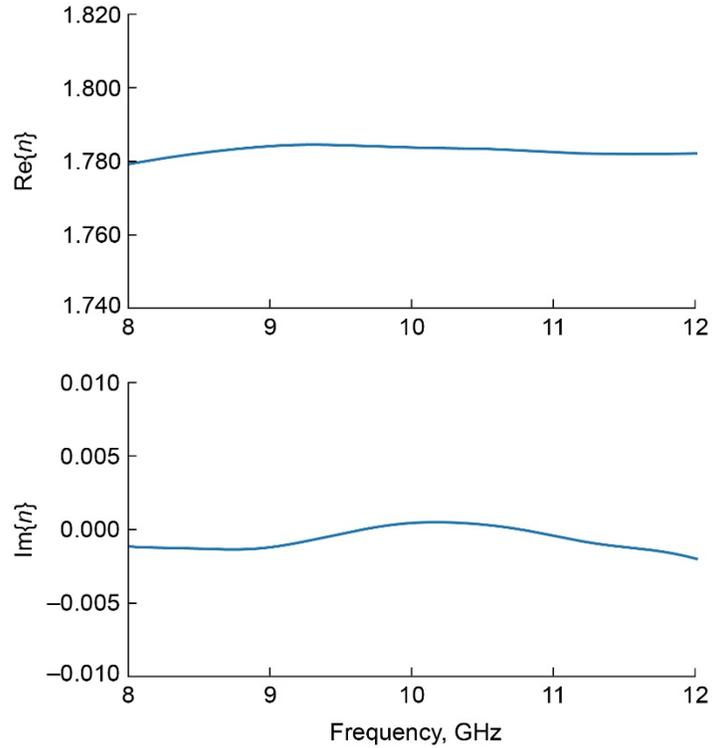


Figure 2.—Measurements of PEEK 450G refractive index n across X-band frequencies. (a) Moderate real component $\text{Re}\{n\}$. (b) Near-zero imaginary component $\text{Im}\{n\}$, indicating minimal transmission loss.

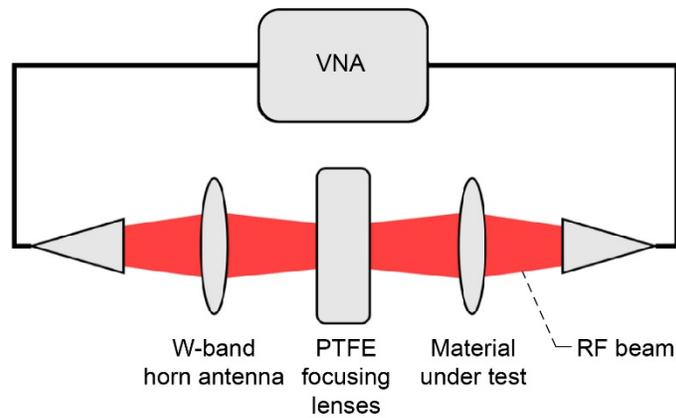


Figure 3.—Test setup to measure W-band scattering parameters from PEEK 450G samples, utilizing vector network analyzer (VNA), two horn antennae to propagate radiofrequency (RF) beam through a pair of polytetrafluoroethylene (PTFE) focusing lenses.

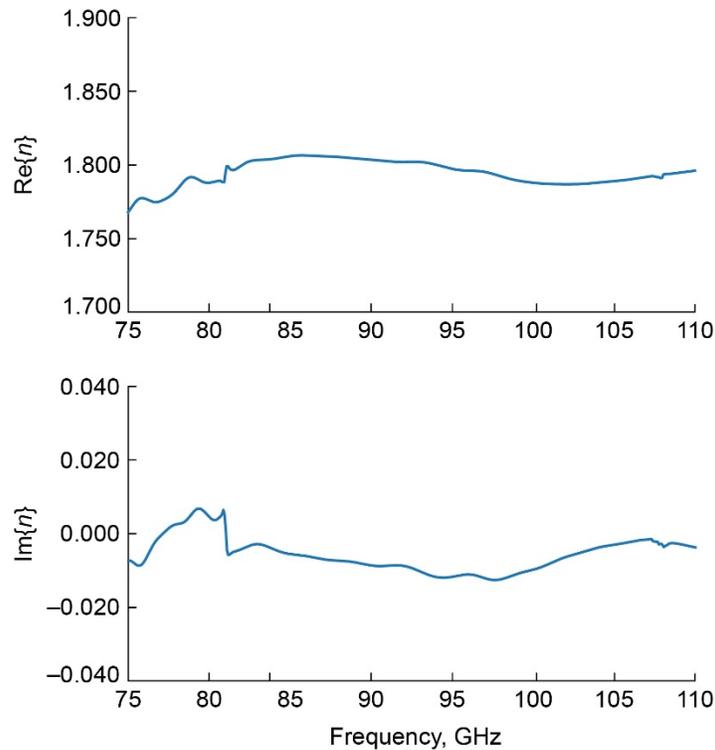


Figure 4.—Measurements of PEEK 450G refractive index n across W-band frequencies. (a) Real component $\text{Re}\{n\}$. (b) Near-zero imaginary component $\text{Im}\{n\}$, indicating minimal transmission loss.

S-parameter data from PEEK 450G samples may now be collected. For these experiments the sample thickness is 3.1 mm. Figure 4 displays the refractive index results calculated using the NRW algorithm from Section 2.0. For this experiment it was necessary to force $u_r = 1$. Regardless, results indicate that the average value of the refractive index value, across the W-band is $n = 1.792 - 0.007i$. The real component is similar to that at X-band frequencies, whereas the imaginary component indicates a higher transmission loss. This is expected considering the order-of-magnitude increase in frequency from X- to W-band.

4.0 Conclusion

To the best of our knowledge, this report presents the first determination of the refractive index of the polyaryletherketone Victrex[®] PEEK 450G at W-band frequencies (75 to 110 GHz). The report also validates previous measurements at lower radiofrequencies (RFs). This work confirms that PEEK 450G is a suitable candidate for NASA’s submillimeter RF-based nondestructive evaluation (NDE) technology. The material has a moderate real refractive index component and exhibits minimal transmission loss as indicated by $n = 1.792 - 0.007i$. Because of the low transmission loss, an exact determination of the loss tangent will require a cavity resonator approach. For the purpose of this report however, determining that the transmission loss through PEEK 450G is small is sufficient.

Moving forward, NASA will continue developing its submillimeter NDE techniques, using PEEK as a validation material. Results from this work will help to design, manufacture, and certify nonmetallic aerospace vehicle components so that they are lighter, safer, and less expensive.

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