Determination Of Optical Constant of a Clear Glass Material for Accurate Daylighting and Solar Heat Gain Assessment Using Spectrophotometer Measurements

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Abstracts: Many qualities make glass attractive, as it is transparent, chemically inert, environmentally friendly, sustainable, strong, easily available and relatively cheap. Recently, many researchers have been interested in designing the buildings to get the benefit from daylight inside, which saves a lot of building consumption for artificial lighting, which gives visual and thermal comfort and also contributes to reducing costs. The complex refractive index of glass is a very crucial concept because it determines not only how much light is reflected and transmitted, but also its angle of refraction in glass. The optical constants of glass material are very useful for determining its radiative properties, as well as for selecting the appropriate thin-film coatings on a glass substrate. The objective of this study is to calculate the real part (*n*) and the imaginary part (*k*) of the complex refractive index of a clear glass material using a simple method based on the reflectivity and transmissivity measurements. In this study, the parts *n* and *k* are derived from the equations of the reflectivity at near zero incidence and transmissivity at normal incidence by using Shimadzu IR-70 Spectrophotometer and Cary 5E Spectrophotometer apparatuses. The real and the imaginary parts of the complex refractive index of the glass sample obtained in the present study are in very good agreement with Rubin's data. Although, a direct comparison between different samples is not possible, due to the difference in manufacturing process and material composition.

Keywords: Complex Refractive Index, Glass Material, Optical Constants, Sustainability, Spectrophotometer.

1. INTRODUCTION

The building façades design has immense influence on daylighting, solar heat gain and natural ventilation, which are closely related to the lighting and air conditioning energy consumption for a building. Therefore, windows must be carefully designed to control the solar gains to suit different climatic regions and orientations. Glass can be defined as an amorphous solid. An amorphous solid is considered to have a random arrangement of atoms, similar to that of molecular arrangements observed in a gas. Glass plays an essential role in science and industry; it is a part of our everyday lives. Familiarity with a few fundamental optical properties helps engineers decide if the glass is the ideal material for the application at hand.

The optical properties of glass determine how it interacts with light. The refractive index is probably the most common optical property. It is defined as the ratio of the speed of light in a vacuum to that of light in a particular material. Light's speed is reduced when it travels through a medium due to the interaction of photons with electrons.

The refractive index is often reported as single number. In reality, refractive index is a complex number comprised of a real part (*n*) and an imaginary part (*k*). The real part, describes the speed of light in the material. The imaginary part of the refractive index is the extinction coefficient in the material - a measure of how much light is being absorbed at a given wavelength. Both *n* and *k* are wavelength dependent, so they vary over the spectrum.

Glass is a hard, typically transparent or translucent, brittle substance. It is made by fusing sand with soda and lime, along with other ingredients if specific properties are required, and cooling rapidly. Architectural glass comprises of silica, lime, and solid carbonate—raw materials that are easily found in nature [1]. In general, the glass material is considered to be transparent for the solar region and opaque for the infrared radiation. In fact, glass material is as an absorbing-emitting medium in the infrared region of the spectrum, with thermal properties determined by the wavelength and angle of incidence of the incoming radiation, respectively denoted as real (*n*) and imaginary (*k*) components of the complex refractive index of glass [2-4]. Therefore, a comprehensive set of optical constants of glass material is essential to assess accurately the heat and the light through the glass layers.

Optical properties of any material can be described via the complex refraction index, elucidating in detail both the method and the apparatus required for determining the optical constants of materials and thickness of thin films [5]. Uehara reported the optical glass characterized by optical constants of refractive index (n_d) within the 1.6−1.69 range, an Abbe number (V_d) ranging from 35 to 45, and a low glass transmission point (T_g), making it suitable for mold press forming [6]. Laser processing of work pieces containing low-k dielectric material has been detailed in [7]. Moreover, Weber reports the use of novel glass material comprising of rare earth aluminate glass in the gain medium of solid-state laser devices that produce light at infrared wavelengths, typically in the 1000 *nm* range, with applications in the infrared optics with transmission to approximately 5000 *nm* [8]. Environmentally-friendly optical glass with rare earth material content with a refraction rate of 1.65−1.75 and the Abbe number in the 50−60 range has been reported in [9].

More recent researches reported some studies related to the thin film materials. Mekhanache et al. [10] studied the effect on natural substrate on the properties of *ZnO* thin films deposited on the glass. All models indicate that the refractive index decreases with increasing energy band. Shabaan et al. [11] reported different compositions of amorphous *Ge15Se85-X* thin films deposited on the glass substrates by the thermal evaporation technique. The optical constant (n, k) of the thin films were obtained by spectroscopy. Prakash et al. [12] studied Zinc telluride (ZnTe) and Zinc Sulfiride (*ZnS*) thin films which have been deposited onto glass substrates by the thermal evaporation technique and the film thickness and the refractive index n of *ZnTe* and *ZnS* were obtained by spectrophotometer and spectroscopic ellipsometry.

Several research groups have developed well adapted deposition procedures to modify the optical properties of the substrate, which include sputtering [13], laser ablation [14] chemical vapor deposition [15], sol–gel [16] and thermal evaporation [17]. Rubin has determined n and k values of clear, low-iron and tinted glass materials using the Kramers-Kronig (*KK*) formula [18]. This technique is highly beneficial in the range characterized by strong absorption and is based on measuring the reflectance of a sample at near normal incidence. The main shortcoming of the *KK* analysis stems from the need for extrapolation in the spectral region for which no data exist [19, 20]. The index of refraction of SiO2 has been also calculated accurately via the prism data method in the low absorption region [19]. Several techniques and experimental methods for determining the optical constants of glass materials are also described in extant literature [21]. Begley has determined *n* and *k* of a glass material using a soda-lime-silica as a test specimen [21]. Clear, low iron and tinted glasses contain absorbers to reduce solar transmittance. The complex refractive index, its imaginary part in particular, is strongly affected by the material iron oxide content. Therefore, a direct comparison between different samples is not possible, due to the difference in manufacturing methods and material composition.

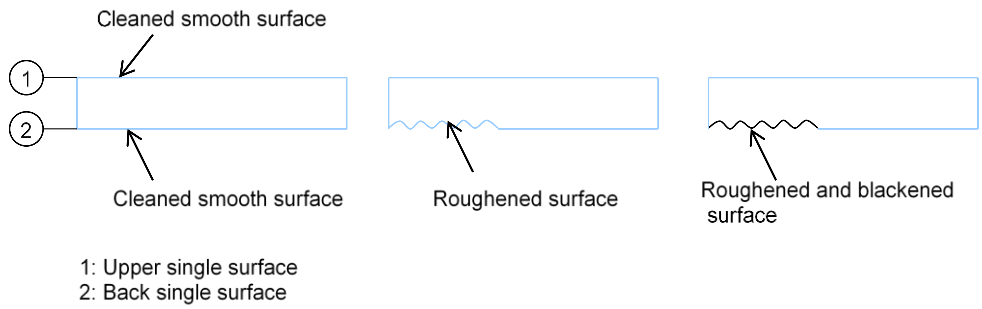
This work reports on a simple and straightforward method for calculating the real and imaginary parts of the complex refractive index of a clear glass material in the ultraviolet to the near infrared range, using the measurement of the reflectivity at near zero incidence and the transmissivity at normal incidence. The real and imaginary parts of the complex refractive index are derived from the reflectivity and transmissivity equations. This information is important for determining the radiative properties of glass material as well as for designing appropriate thin-film coatings on a glass substrate for daylighting and solar heat gain.

2. MATERIEL AND METHODS

The reflectivity and the transmissivity measurements were performed using Shimadzu IR-70 Spectrophotometer, which measures the reflectivity and the transmissivity of a sample in the 2.5−20 μm range. The specular and diffuse reflectivity, as well as direct plus diffuse transmissivity from 0.19 μm to 2.5 μm for the diffuse component, and from 0.19 μm to 3.3 μm for the direct specular component have been measured using the Cary 5E Spectrophotometer apparatus. In this work, all transmission measurements were performed in the standard transmission mode, rendering the diffuse component negligible.

The thickness of the sample utilized in this work was 1.79 mm. The sample was cleaned with ethanol few minutes prior to commencing the experiment to avoid having any impurities on its surface that would compromise measurements. The transmissivity measurement was carried out on the cleaned-smooth surface of the glass material at normal incidence.

Three reflectivity measurements were performed. The first measurement was carried out on the smooth upper single surface of the glass (it should be noted that the back surface was smooth as well, as shown in Fig. 1 (a)). Prior to the second measurement, the back surface of the sample was partially scratched to eliminate multiple reflections in the transparent region below 5 μm (Fig. 1 (b)), and the measurement was performed at the smooth surface opposite to the roughened one. Finally, the scratched surface was blackened, and the third reflectivity measurement was carried out at the same smooth upper single surface (Fig. 1 (c)).



(a) Both upper and back surfaces are smooth surface

(b) Sample with upper smooth and back roughened surface

(c) Sample with upper smooth and back roughened and blackened surface

Figure 1. State of the surface of the sample

3. EXPERIMENTAL RESULTS

Figure 2 shows the reflectivity measurement curves as a function of changes in the wavelength from the ultra-violet to the very near infrared (0.19−2.5 μm) values, obtained by using Cary 5E Spectrophotometer. The high signal-to-noise ratio of this instrument allows precise measurement of even very small reflectivity values in this range. The average value of the noise measurement was obtained and was incorporated into the calculation. The reflectivity curves shown in Fig. 2 appear to be a function of *n* and exhibit gradual change in this range. As can be seen, while the two smooth glass surfaces reflect around 8% of the incident beam, this value declines by 50% when the back surface of the sample is scratched. Moreover, when the back surface is roughened and blackened, the reflectivity measurement is lower than that obtained without the black color, particularly in the solar range. This decline is caused by light scattering, whereby the rays remain inside the glass and are superimposed on the reflectivity pertinent to the first interface.

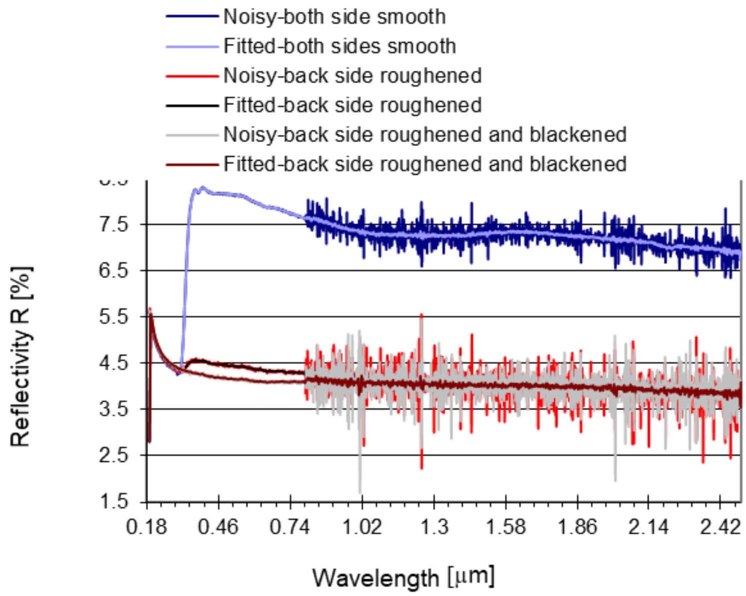


Figure 2. Reflectivity measurements at near zero incidence from 0.19 to 2.5 *μm*

Figure 3 shows the reflectivity measurements as a function of wavelength changes in the infrared range of the spectrum, obtained by Shimadzu IR-470 Spectrophotometer apparatus. The three curves are indistinguishable and appear to be strongly dependent on *k*. The transmissivity measurement of the glass material at normal incidence, which is negligible beyond 5 *μm*, is shown in Figure 4. Therefore, the glass is considered opaque in the infrared range beyond 5 *μm*.

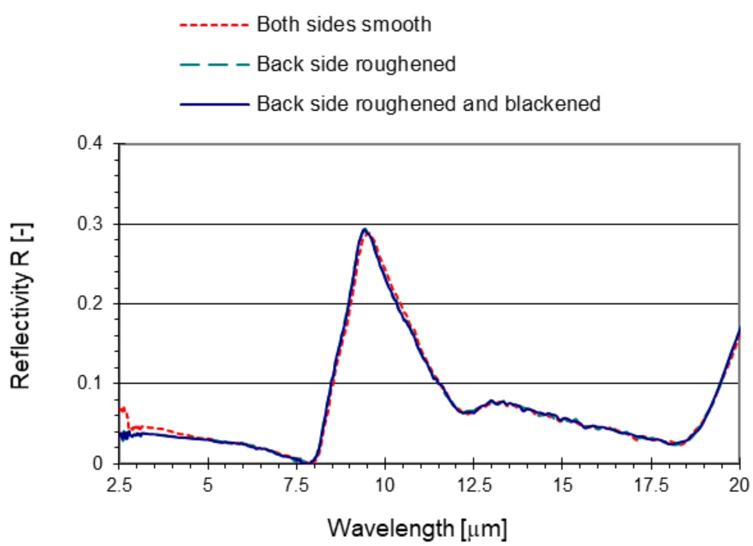


Figure 3. Reflectivity measurements at near zero incidence from 2.5 to 20 *μm*

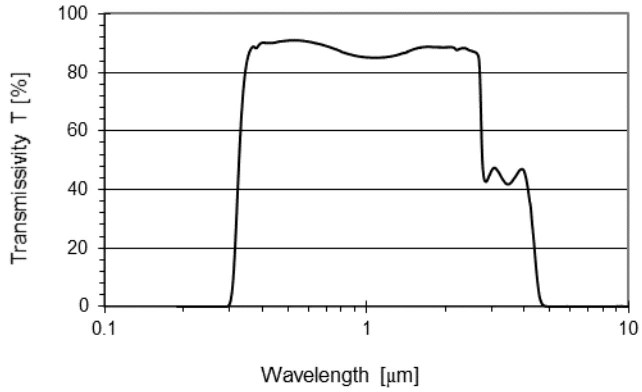


Figure 4. Transmissivity measurement at normal incidence

4. METHOD OF CALCULATION AND RESULTS

The complex refractive index of the glass (comprising of real and imaginary components *n* and *k*) is derived from the reflectivity and transmissivity equations, pertinent to near zero and normal incidence measurements, respectively. The fraction transmitted through the glass was obtained by using Siegel method, i.e., through partially transparent plates [21]. Figure 5 shows the model of the net radiation method applied for a glass material subjected to the unit incident radiation *q*. It should be noted that the sample was sufficiently thick to render the interference effects negligible.

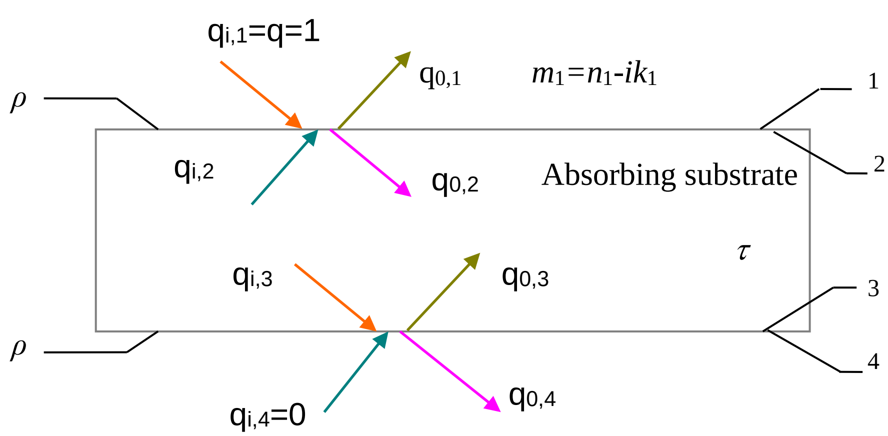


Figure 5. Model of the net radiation method applied for glass material

The outgoing flux at each interface can be expressed in terms of the incoming fluxes, to yield the following equations for the conditions of a unit incoming flux at surface 1 and zero incoming flux at surface 4 [22].

$$\begin{aligned} q_{0,1} &= \rho + (1-\rho)q_{i,2} \\ q_{0,2} &= (1-\rho)q_{i,1} + \rho q_{i,2} = (1-\rho) + \rho q_{i,2} \\ q_{0,3} &= \rho q_{i,3} + (1-\rho)q_{i,4} = \rho q_{i,3} \\ q_{0,4} &= (1-\rho)q_{i,3} + \rho q_{i,4} = (1-\rho)q_{i,3} \end{aligned} \quad \textbf{(1)}$$

The transmittance of the layer is used to relate the internal q_i and q_o to yield

$$q_{i,2} = q_{0,3}\tau$$

$$q_{i,3} = q_{0,2}\tau \quad (2)$$

Solving the above equations provides the fraction transmitted through the glass material, i.e.,

$$T_r = \frac{(1-\rho)^2\tau}{1-\tau^2\rho^2} = q_{0,4} \quad (3)$$

where ρ and τ are the reflectivity at single interface and the internal transmittance of the glass pertaining to the internal absorption only, respectively. for a single interface with scratched and blackened back surface, the following holds:

$$\rho = R \quad (4)$$

where *r* is the measured reflectivity.

The internal transmittance is given by Siegel [14]

$$\tau = exp[(-4\pi k)/\lambda\, d] \quad (5)$$

where d and λ are the sample thickness and the wavelength of incident light, respectively. from equation (3), the following second-order equation in τ can be derived

$$T_r R^2\tau^2 + (1 - R^2)\tau - T_r = 0 \quad (6)$$

The positive solution of the above equation is

$$\tau = \frac{-(1-R^2)+\left[(1-R^2)^2+4T_r{}^2R^2\right]^{0.5}}{2T_rR^2} \quad (7)$$

Thus, the value of k can be derived from equation (5)

$$k = \frac{-\lambda}{4\pi d}\log\tau \quad (8)$$

The reflectivity at the interface between two absorbing media at normal incidence is expressed in terms of the complex refractive indices of the two media and is given by siegel [23]

$$R = \frac{(n_2-n_1)^2+(k_2-k_1)^2}{(n_2+n_1)^2+(k_2+k_1)^2} \quad (9)$$

where $m_1 = n_1 - ik_1$ and $m_2 = n_2 - ik_2$ are the complex refractive indices of air and glass material, respectively. since the incident ray travels through air ($k_1 = 0$ and $n_1 = 1$), the reflectivity at normal incidence is given by

$$R = \frac{(n-1)^2+k^2}{(n+1)^2+k^2} \quad (10)$$

where $n = n_2$ and $k = k_2$ are the real and imaginary parts of the complex refractive index of the glass material, respectively. arranging equation (10) in terms of n, yields the following expression

$$n^2(1 - R) - 2n(1 + R) + (1 - R)(k^2 + 1) = 0 \quad (11)$$

Solving the above equation in n provides the real part given by

$$n = [Q^2 - (k^2 + 1)]^{0.5} + Q \quad \textbf{(12)}$$

where

$$Q = \frac{1+R}{1-R} \quad \textbf{(13)}$$

The method described above is direct and simple to use, as it relies on the reflectivity and the transmissivity measurements only. however, its application is limited to the wavelengths below 5 *μm*, as beyond this value n and k cannot be obtained due to the small t_r (see equation (7)). Rubin reported that the principal effect of the chemical differences among clear, low iron, and other kinds of tinted glasses occurs in the visible and very near infrared range. The variation in the transmittance and the reflectance of these glasses is more pronounced in the solar region than in the infrared part of the spectrum due to the presence of *feo* in the raw materials added to control the melting point [18]. The real and imaginary parts of the complex refractive index of the glass material in the near infrared and far infrared regions (5 to 300 *μm*) are determined by Rubin [18] and these values can be used for tinted glass as well.

the optical constants n and k of the clear glass material in the 0.19 to 5 *μm* region are plotted in fig. 6 and provided in table 1. as can be seen, both n and k are in good agreement with the data reported by Rubin

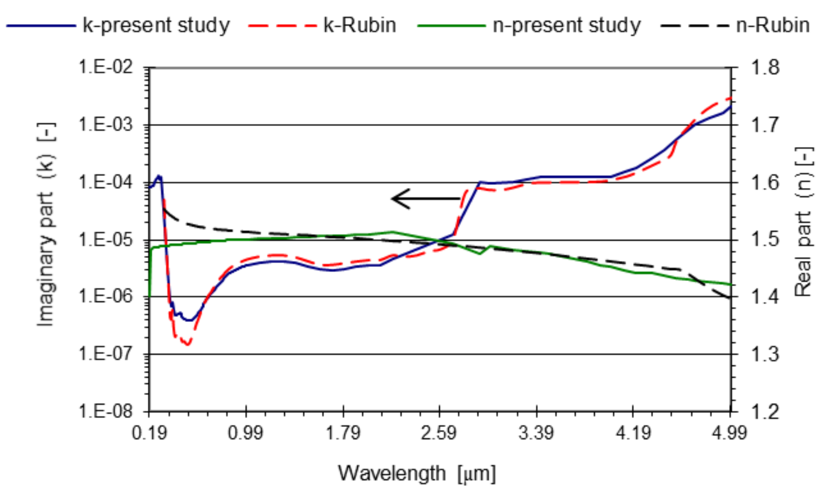


Figure 6. Optical constants of a clear glass material from 0.19 to 5 µm

Table 1. Optical Constants of a Clear Glass Material from 0.19 to 5 *μm*

λ [μm]	*n [-]*	*k [-]*	*λ [μm]*	*n [-]*	*k [-]*	*λ [μm]*	*n [-]*	*k [-]*
0.19	1.403	8.168E-05	0.57	1.494	4.537E-07	0.96	1.500	3.417E-06
0.20	1.483	8.304E-05	0.58	1.495	4.777E-07	0.97	1.500	3.480E-06
0.21	1.485	8.841E-05	0.59	1.495	5.244E-07	0.98	1.500	3.516E-06
0.22	1.486	8.875E-05	0.60	1.495	5.560E-07	0.99	1.500	3.575E-06
0.23	1.487	9.969E-05	0.61	1.495	6.008E-07	1.00	1.501	3.633E-06
0.24	1.487	1.143E-04	0.62	1.495	6.564E-07	1.10	1.501	4.070E-06
0.25	1.488	1.206E-04	0.63	1.496	7.072E-07	1.20	1.502	4.283E-06
0.26	1.488	1.284E-04	0.64	1.496	7.510E-07	1.30	1.503	4.225E-06
0.27	1.488	1.122E-04	0.65	1.496	8.193E-07	1.40	1.504	3.931E-06
0.28	1.488	1.163E-04	0.66	1.496	8.744E-07	1.50	1.505	3.348E-06
0.29	1.488	1.254E-04	0.67	1.496	9.313E-07	1.60	1.506	3.000E-06
0.30	1.489	6.540E-05	0.68	1.497	9.895E-07	1.70	1.507	2.881E-06
0.31	1.489	3.251E-05	0.69	1.497	1.077E-06	1.80	1.508	3.084E-06
0.32	1.490	1.540E-05	0.70	1.497	1.148E-06	1.90	1.508	3.320E-06
0.33	1.490	7.031E-06	0.71	1.497	1.222E-06	2.00	1.510	3.497E-06
0.34	1.490	3.225E-06	0.72	1.497	1.298E-06	2.10	1.512	3.537E-06
0.35	1.490	1.581E-06	0.73	1.497	1.375E-06	2.20	1.514	4.599E-06
0.36	1.490	9.156E-07	0.74	1.498	1.477E-06	2.70	1.493	1.238E-05
0.37	1.491	6.874E-07	0.75	1.498	1.566E-06	2.92	1.475	9.998E-05
0.38	1.491	8.085E-07	0.76	1.498	1.667E-06	3.01	1.489	9.434E-05
0.39	1.491	5.839E-07	0.77	1.498	1.755E-06	3.20	1.483	1.018E-04
0.40	1.491	4.722E-07	0.78	1.498	1.841E-06	3.31	1.480	1.128E-04
0.41	1.491	4.813E-07	0.79	1.498	1.956E-06	3.42	1.478	1.231E-04
0.42	1.492	5.148E-07	0.80	1.499	2.112E-06	3.51	1.476	1.272E-04
0.43	1.492	5.181E-07	0.81	1.499	2.202E-06	3.60	1.471	1.275E-04
0.44	1.492	5.303E-07	0.82	1.499	2.303E-06	3.70	1.466	1.253E-04
0.45	1.492	5.061E-07	0.83	1.499	2.381E-06	3.81	1.463	1.226E-04
0.46	1.492	4.618E-07	0.84	1.499	2.470E-06	3.92	1.456	1.222E-04
0.47	1.493	4.366E-07	0.85	1.499	2.573E-06	4.00	1.452	1.267E-04
0.48	1.493	4.195E-07	0.86	1.499	2.643E-06	4.12	1.447	1.514E-04
0.49	1.493	4.123E-07	0.87	1.499	2.748E-06	4.21	1.442	1.817E-04
0.50	1.493	3.981E-07	0.88	1.500	2.821E-06	4.35	1.441	2.655E-04
0.51	1.493	3.908E-07	0.89	1.500	2.916E-06	4.44	1.438	3.752E-04
0.52	1.494	3.884E-07	0.90	1.500	2.974E-06	4.55	1.434	5.603E-04
0.53	1.494	3.883E-07	0.91	1.500	3.058E-06	4.65	1.431	8.397E-04
0.54	1.494	3.982E-07	0.92	1.500	3.134E-06	4.71	1.429	1.005E-03

0.55	1.494	4.078E-07	0.93	1.500	3.213E-06	4.82	1.426	1.320E-03
0.56	1.494	4.297E-07	0.94	1.500	3.278E-06	5.00	1.422	2.081E-03

CONCLUSIONS

A simple method to determine the optical constants in the 0.19−5 *μm* range was described. Sample reflectivity and transmissivity in the 2.5−20 *μm* range were measured using Shimadzu *IR-70* Spectrophotometer, while *Cary 5E* Spectrophotometer apparatus was employed for specular and diffuse reflectivity measurements, along with direct plus diffuse transmissivity from 0.19 *μm* to 2.5 *μm* for the diffuse component, and from 0.19 *μm* to 3.3 *μm* for the direct specular component.

The real (n) and imaginary (k) parts of the complex refractive index of the glass material were derived from the reflectivity and transmissivity equations, at near zero and normal incidence, respectively. The back surface of the sample was roughened to prevent multiple reflections, as well as blackened to avoid superimposition of the scattering light onto the reflectivity pertinent to the first single interface. Both n and k values are in good agreement with Rubin's data. This approach will be extended to other glass material types, including tinted glasses with thin coating.

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