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Snapshot refractive index measurement of a liquid medium based on spatial division of a diffraction grating

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Abstract

This study describes a low-cost snapshot refractive index measurement method based on a spatial separation of diffraction patterns from a diffraction grating. The proposed new device employs a vertical line-shaped laser light source and a transmissive diffraction grating for the spatial separation of the diffraction pattern. It enables the measurement of the refractive index of an unknown liquid easily, quickly, and accurately. More importantly, it enables the simultaneous measurement of the refractive index of multiple liquids in one-shot. In this study, a length-based refractive index measurement method is described. Experiments using two different liquids were performed to demonstrate the feasibility and accuracy of the device. The experimental results showed that the proposed device provided an affordable solution for educational purposes as well as for practical refractive index measurement applications such as water quality monitoring.

Keywords

Refractive index, Snapshot measurement, Diffraction grating, Spatial division, Liquid medium

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1 Introduction

The refractive index of a material is an important parameter, as it determines potential uses in optics and materials science (1). Refractive index measurement is among the most fundamental and significant measurement technologies (2-8). It has been applied in various fields, such as in pharmaceuticals, food, and life science, to measure the refractive index of liquids, solids, and gases. The most representative method of measuring refractive index is by using the principle of refraction, which occurs when light passes through another medium (2-4). In addition, various methods using diffraction gratings and interferometers have been proposed (5-8). They typically measure the refractive index at a specific wavelength by measuring the refraction and diffraction angles with a precision of ~ 0.005. Although the diffraction method has the inherent benefit of higher precision than the refraction method, accurate refractive index measurement using the diffraction scheme requires prior knowledge of the refractive index of optical elements used to make the optical system or additional devices to measure the rotation angle of the diffraction grating. Thus, typical commercialized refractometers use the principle of refraction rather than diffraction. Multiple studies have been performed to provide high-precision solutions (5-8). Among them, Singh (2) introduced a cost-effective and simple approach for refractive index measurement by employing two lasers and two diffraction gratings, to quickly assess contamination levels in diverse surface water sources crucial for drinking water in Africa.

Our study introduces a budget-friendly technique enabling the simultaneous, single-shot measurement of refractive index for multiple liquids with enhanced ease, speed, and precision compared to conventional methods employing diffraction gratings. The primary objective is to offer an accessible method meant to be used in the educational setting while addressing practical challenges encountered in areas with limited water quality monitoring resources, thereby aiming to facilitate efficient liquid refractive index measurement in these situations. The proposed scheme needs only a single image to calculate the refractive index of an unknown liquid, while most previous studies are based on two-shot measurements; one for air measurement, and the other for the unknown liquid measurement. The proposed scheme does not require accurate information about a diffraction grating pitch. Neither does it require information on the specific laser wavelength used. This simplifies the calculation of the refractive index of an unknown liquid compared with the previous studies, that do require this information to calculate the index. The single-snapshot capability is enabled by employing a line-shaped laser. The proposed scheme can be extended to simultaneously measure the refractive index of multiple unknown liquids.

2 Materials and Methods

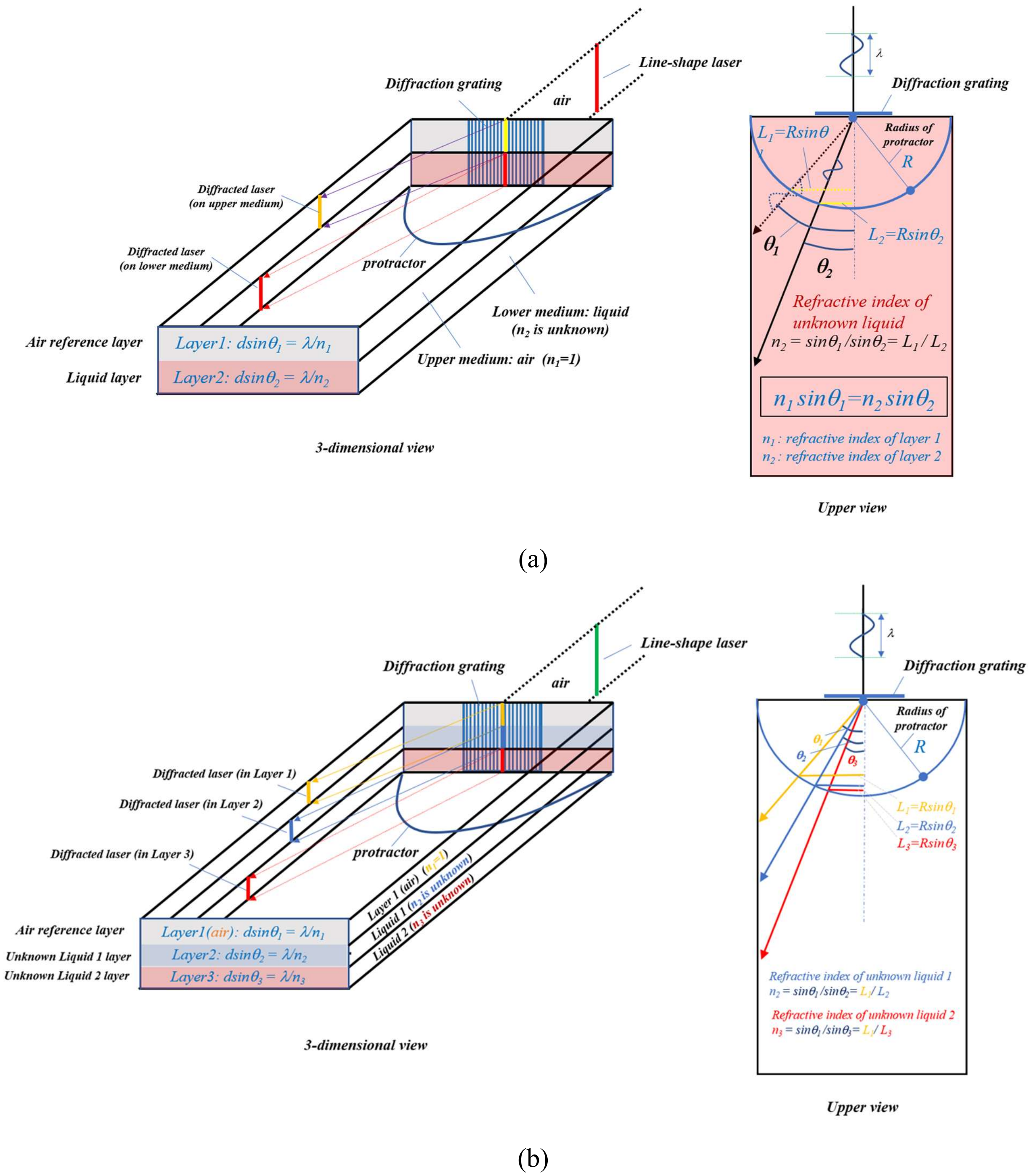


Figure 1. Schematic of the proposed snapshot refractive index measurement setup: for a single liquid (a) and for dual/multiple liquid measurements (b).

Figure 1(a) shows a schematic of the single-snapshot liquid refractive index measuring device using the spatial separation of a diffraction grating, which can precisely measure the refractive index of a liquid using a single photographic image. The proposed system employs a line-shaped laser light source (wavelength changeable to R (red), G (green), B (blue), etc.), a transmissive diffraction grating (periodic grid spacing: 2 μm), and a cubic vessel (dimensions of 100 (width) x 200 (length) x 40 (height) (mm^3)) that contains the measurement liquid or liquids. The vertically mounted line-shaped laser is positioned so that the light impinges at the center of the diffraction grating, as illustrated in Figure 1(a). A protractor is mounted on the bottom of the vessel to check the laser's diffraction angle. Translucent tapes are attached to all the bottom surfaces of the container other than the protractor area to increase the visualization of the diffracted light. Figure 1(b) shows a modified schematic of the single-snapshot liquid refractive index measuring device for simultaneous dual-liquid measurement. The two different liquids are separated spatially by a transparent glass plate placed between the two liquid mediums. Through the spatial-division approach, the proposed single-snapshot scheme can be extended to measure the refractive index of multiple unknown liquids.

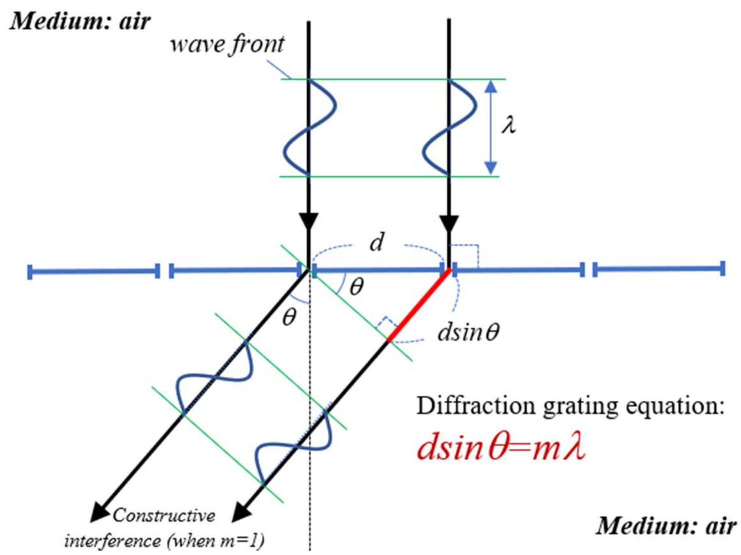


Figure 2. Description of transmission diffraction grating equation.

Figure 2 is a diagram depicting the principle of diffraction that occurs when a monochromatic wave travels through a transmissive diffraction grating. Constructive interference is created when the optical path difference (red line) meets the condition of the relationship between the diffraction angle (θ), the diffraction grating spacing (d), and the wavelength λ. The diffraction angles θ at which the constructive interference is generated can be calculated according to equation 1, where *m* is an integer. In this study, *m*=1. In other words, the first-order diffraction angle (θ) has a sine function relationship with the ratio of the wavelength of incident light (λ) and the diffraction grating spacing (d).

$$d sin\theta = m\lambda \qquad (1)$$

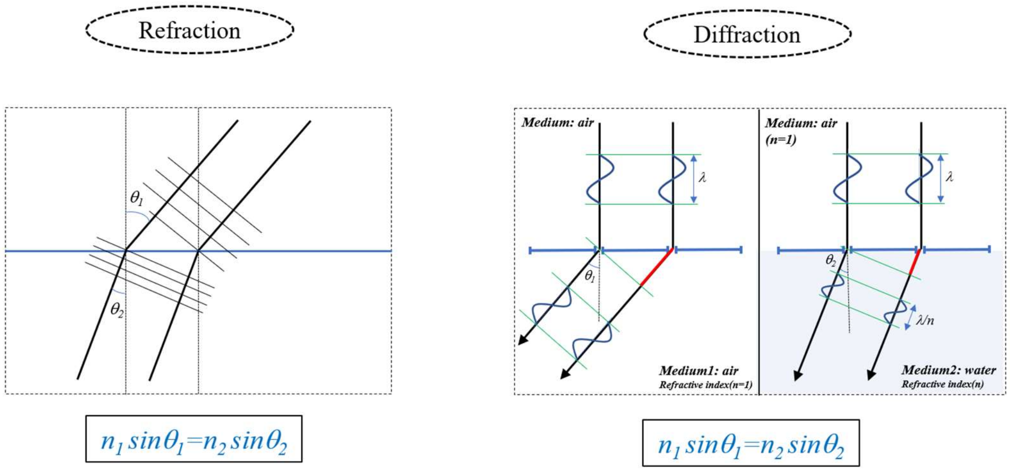


Figure 3. Equation similarity between refraction and diffraction.

Figure 3 (a) depicts Snell's law - the law of refraction - where the two angles (θ_1, θ_2) represent the angle of incidence and refraction of light for different media, and the two indices of refraction (n_1, n_2) are the refractive index of the incident medium and that of the refractive medium, respectively. Figure 3 (b) visually represents how the diffraction angle (θ_1, θ_2) changes when light is incident perpendicular to the diffraction grating. Similar to the refraction phenomenon shown in Figure 3 (a), the wavelength (gap distance between the two consecutive wavefronts) is narrowed when light travels from air to water, or from a medium of lower refractive index to a medium with a higher refractive index. In the diffraction phenomenon, as illustrated in Figure 3 (b), after the light passes through the diffraction grating, the upper part then travels through air and the lower part(s) travel through the liquid or liquids whose refractive indices are to be measured. The relationship between the diffraction angles (θ_1, θ_2) determined by the change in the refractive index of the medium (Figure 3(b)) can be expressed by the same equation as Snell's law (Figure 3(a)). As the refractive index of water can be obtained by measuring the angle of incidence and refraction using Snell's law where the first medium is air and the second medium is water, similarly, the refractive index of water can be obtained by using the angle of diffraction in air and the angle of diffraction in water using the same equation as that presented in Figure 3 (b). In Snell's law, the incident angle in medium 1 is determined arbitrarily, while the diffraction angle is determined by the ratio of the wavelength of light and the diffraction grating spacing.

Both refraction and diffraction phenomena describe how light bends based on the medium it travels through. They also have mathematical similarities, as shown in Equation 2. However, the working principles differ for the two phenomena.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{2}$$

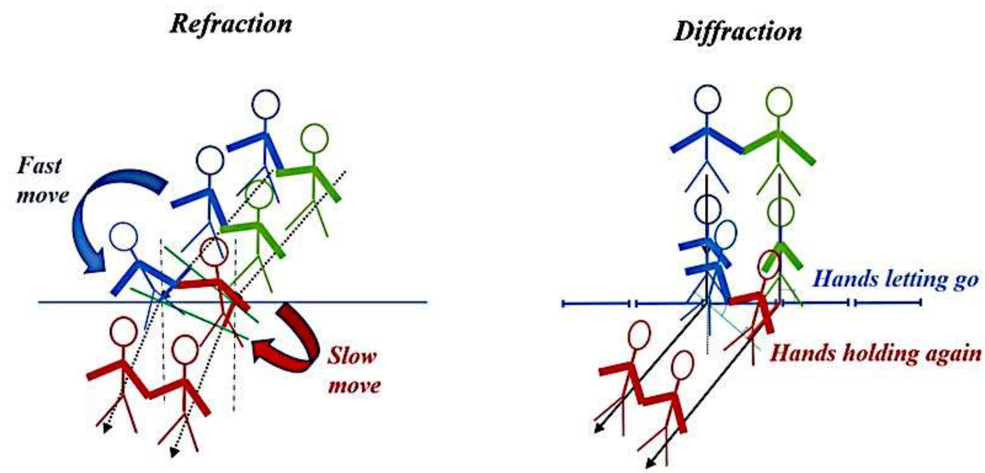


Figure 4. Conceptual representation of the bending phenomenon of light when refracted through another medium (a) and when diffracted (b), through an aperture (diffraction grating).

The refraction phenomenon may be thought of as being analogous to people walking side by side holding each other's hands, as shown in Figure 4 (a), where they need to adjust their stride length (adjust their speed) appropriately to pass through the new medium, so as to keep walking while holding each other's hands. On the other hand, the bending of light due to the diffraction phenomenon that occurs at the diffraction grating is akin to people holding hands while passing through the diffraction grating momentarily releasing their hands to change direction, and then, holding hands with a person next to you who was one step ahead of you, as shown in Figure 4 (b). To measure the refractive index of liquid samples more easily and more precisely than existing methods, in this study, a one-time measurement was used (one photographic image) based on the principle of diffraction angle change associated with the change in the medium located after the diffraction grating, as depicted in Figure 3 (b).

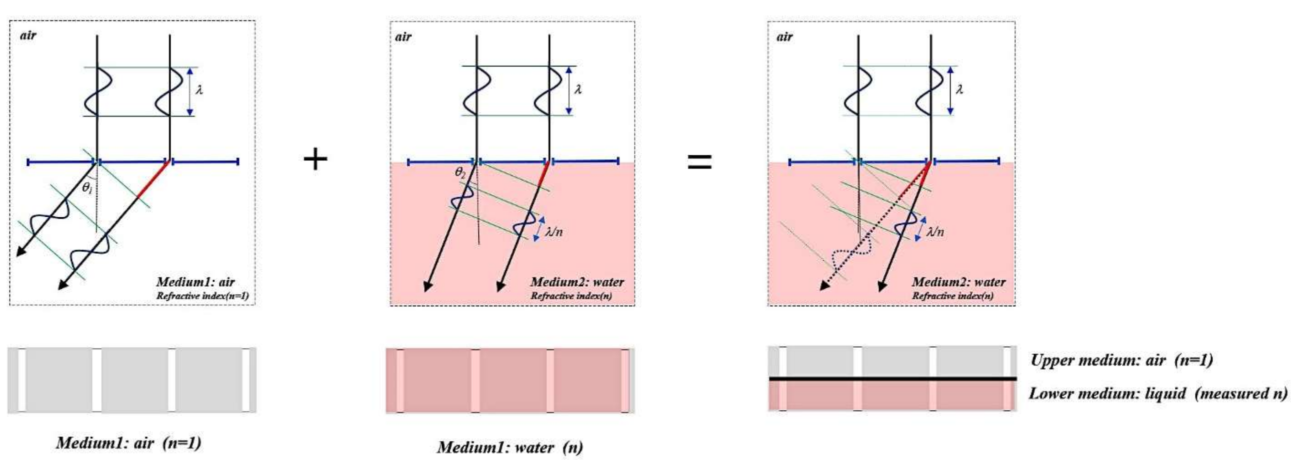


Figure 5. Simultaneous diffraction angle measurement based on space-division of a transmissive diffraction grating.

Figure 5 shows the principle of simultaneously observing diffraction phenomena occurring in two different media through spatial separation of a transmission-type diffraction grating. Figure 5 (a) represents a schematic diagram of the progression of the first diffraction light as seen from the top when the medium through which the diffraction light travels after the diffraction grating is air, and Figure 5 (b) shows when the medium of the liquid container is changed to pure water. This is a schematic view from the top. Figure 5 (c) shows a schematic view from the top when only 50% of the liquid container is filled with water, and the remaining diffracted light travels through the air medium. One of the important suggestions of this study is the employment of a line-shaped laser light source. Through the combination of the line-shaped laser light source and a transmissive diffraction grating, the diffraction phenomenon of heterogeneous samples with different refractive indices of heterogeneous media can be visually observed simultaneously when imaging with the eye or camera from the top view, as shown in Figure 5 (c).

The snapshot liquid refractive index measurement device presented in this study has a simple structure and an intuitive principle. It provides a new method that allows anyone with high school physics knowledge to easily, quickly, and accurately measure the refractive index of an unknown liquid. This study shows experimentally the possibility of measuring the refractive index of a single unknown liquid sample. However, the refractive index of two or more liquid mediums can be measured through the single-shot scheme by varying the structure of the proposed device as illustrated in Figure 1 (b).

Equation 3 is derived from Equation 2. Figure 6 shows the methodology for measuring the unknown liquid refractive index using the proposed device. In general, length can be measured more precisely than angle. Precision can be further increased by enlarging the size of the device. Using the length-based measurement methodology, the refractive index of an unknown liquid can be measured as per equation 3.

$$n_2 = n_1 \times \frac{\sin\theta_1}{\sin\theta_2} = n_1 \times \frac{L_1}{L_2} \qquad (3)$$

Where, n_1 is the refractive index of air (n_1=1) and n_2 is the unknown refractive index of the known or unknown liquid. L_1 and L_2 represent the lengths between the 0th and 1st-order diffraction lines as shown in Figure 6. Note that the proposed scheme can provide the single-shot capability even when the laser wavelength and grating pitch are unknown.

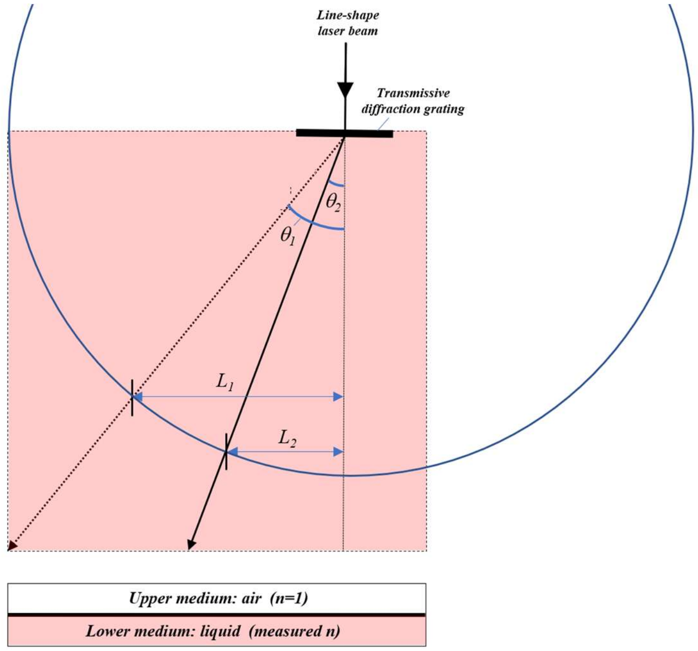
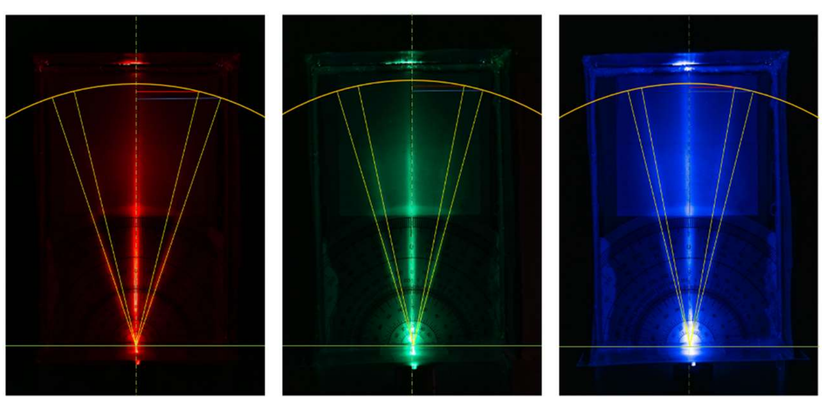


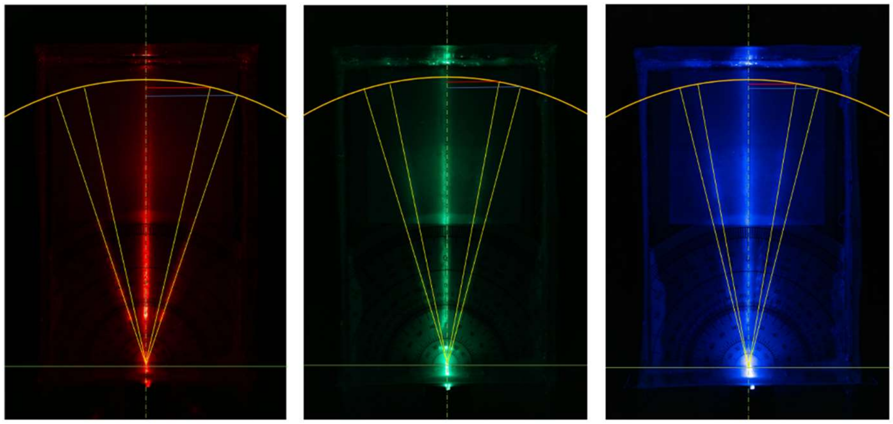
Figure 6. Length-based measurement methodology of the proposed liquid refractive index measurement method.

3 Results and discussion

To verify the single-snapshot performance of the proposed refractive index measurement device, experiments were performed using two different liquids (pure water and an aqueous glucose solution) at a room temperature of 21 ºC ± 3 ºC. The experimental setup consisted of a vertical line-shaped laser light source and a transmissive diffraction grating (periodic grid spacing: 2 µm) mounted on a cubic container with a dimension of 100 (width) x 200 (length) x 40 (height) (mm^3). In this study, the refractive indices of the two different liquids were measured at three different wavelengths of red at 636 nm, green at 517 nm, and blue at 459 nm, for each liquid sample by replacing the three laser light sources sequentially, while leaving the transmissive diffraction grating attached to the sample container undisturbed.



(a)



(b)

Figure 7. Captured photographs of (a) pure water and (b) glucose water taken for the RGB line laser.

To obtain reliable images of the diffracted light of the proposed snapshot liquid refractive index measurement device, all the images in Figure 7 were captured by securely fixing the camera used in this experiment. Also, note that the aqueous solution samples need to be carefully prepared so as not to exceed the maximum solubility of the solute in water. Aqueous solutions that contain more solute than can be dissolved will scatter light which can degrade the diffracted beam image quality. The diffraction angles (θ_1, θ_2) in the unknown liquid medium and air were measured simultaneously through the proposed spatial separation of the diffraction grating combined with the line-shape laser source. The refractive index of each liquid sample was precisely measured for each wavelength using the length measurements (L_1, L_2) as the surrogate, as represented in Figure 6. Each photographic image shown in Figure 7 was used to calculate the refractive index using Equation 3.

Figure 8 shows the measured refractive indices of the two liquid samples (pure water and a 50% w/v aqueous glucose solution) at different wavelengths. The refractive index of pure water reported in the literature is 1.3317 at 632 nm, 1.3342 at 520 nm, and 1.3372 at 445 nm. Although the measured refractive index of the pure water using this method differed slightly from the literature data, the measured data showed the tendency for the refractive index to decrease as the wavelength increased. In this experiment, we used a 50% w/v aqueous glucose solution and measured its refractive index at 520 nm. The measured value of 1.45 agreed with that reported in the literature (9). The proposed single-snapshot refractive index measurement device represents a budget-friendly solution with enhanced ease, speed, and precision capabilities when compared with previous methods. The estimated price required to assemble the proposed setup is ~ $50, since it uses the RGB line-shaped laser and a transmission diffraction grating, which are included in the educational optics kit designed and manufactured by the SPIE and the OSA (Optical Society of America). This method can provide an affordable solution for educational purposes and to monitor water quality.

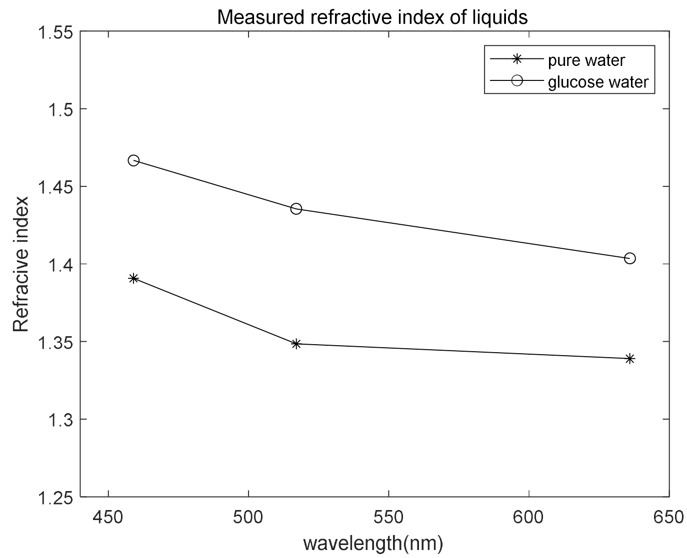


Figure 8. The measured refractive index of the two liquids at the RGB wavelengths.

4 Conclusion

We have proposed a low-cost single snapshot refractive index measurement method that can measure the refractive index of a liquid; or of multiple liquids, using a single diffraction grating easily, quickly, and accurately. The snapshot liquid sample refractive index measurement method using diffraction grating spatial separation presented in this study is a new concept designed to be appropriate for use in high school physics and science education as well as in advanced university physics courses as it has the benefits of convenience of production and intuitiveness of understanding. In addition, this study described the similarity in the theory of refraction and that of diffraction to aid in understanding the method. We anticipate that this study can not only help hands-on education on the interaction between light and matter, but it can be used as an affordable tool to measure water quality. Also, through further iterations, the measurement methodology has potential to be incorporated into a real-time, automated liquid refractive index measurement device for various research and industrial purposes including those encompassing the agricultural, pharmaceutical, and biochemical fields.

5 References

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