Comparison of Image Resolution Limits in Glass and Polymer Waveguides

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Abstract

Augmented reality (AR) waveguides are often treated as flat. However, some roughness present will blur the final image. By comparing the optical system's modulation transfer function (MTF), we find that glass waveguides can transmit higher resolutions than untreated plastic waveguides that require additional manufacturing steps to achieve comparable quality

Author Keywords

Augmented reality; modulation transfer function; image resolution; surface roughness; waveguides

1. Introduction

Augmented reality (AR) is a growing technology that promises to seamlessly integrate digital information with the real-world environment by projecting images to a user's eye while the environment is clearly visible. Many hurdles still exist before the mass adoption of this technology, and it remains a popular topic of research. AR devices face many unique challenges, chief among which includes the method by which an image is projected to the user's eye. A popular method of image projection involves using total internal reflection (TIR) within a waveguide to transfer images from an input coupler near the light engine to an output coupler near the eye.[1] Most simulations and resolution calculations assume that these waveguides are perfectly smooth, but no material is perfectly smooth, and there will always be some level of deviation from an ideal surface. These deviations can vary depending on the material of the waveguide chosen, and how they are processed.

Glass vs Polymer Waveguides: Traditionally, many AR waveguides have been developed using glass waveguides for their sturdiness and higher index, which allows for a large field of view (FOV). In recent years, companies like Cellid and Magic Leap[2,3] have begun to develop waveguides based on polymers rather than glass. They are lower cost, lighter, and can be made into curved waveguides.[3] For the most part, these plastic waveguides are certainly capable of transmitting decent quality images. However, there is a continual push for ever higher resolution light engines that can match the human visual limit of 60 pixels per degree.[4] As the resolution of AR light engines continues to increase, the roughness of these waveguides may significantly reduce the image quality.

Surface Roughness: In many AR displays, the light from a microdisplay is coupled into a waveguide, and it travels through the waveguide via TIR until it hits the output coupler. Microdefects in the waveguide can scatter light, blurring the final image. This effect may not be noticeable in lower resolution displays, or in waveguides with few reflections. As the industry strives for AR devices with higher resolutions, something as simple as the roughness can blur the image enough that it is impossible to reach the human visual limit of 60 pixels per degree.

There are different scales to consider when discussing surface imperfections. Mid-frequency surface deviations (waviness) in a waveguide can be measured simply using interferometry.[5] these are usually well accounted for. The high spatial frequency surface roughness is a factor that may be briefly mentioned, but not always. Despite this, they are still a contributor to surface scattering.[6] These surface deviations often require more complex measurement methods such as atomic force microscopes or SEMs.[7] In a very smooth surface, normal surface roughness levels may not produce significant aberrations in devices where an image interacts with it only one time. However, for an AR waveguide, an image can interact with the same surface dozens of times before it reaches the observer. We must then consider the effects that these imperfections can have on the final image quality. The surface roughness of both polymer and glass waveguides can vary significantly, but in general, glass tends to be smoother than plastic. Plastic, being a softer, easily warped material, is more difficult to polish with conventional methods. It is possible for polymer waveguides to improve their surface roughness, but it requires extra steps in the manufacturing process like spin coating.

Modulation Transfer Function: The MTF describes how the contrast at certain spatial frequencies changes as they pass through an optical system. As with many simple lens systems, the human eye is able to pass lower frequencies to the retina, and the contrast tapers off at higher spatial frequencies. The MTF ranges between 0 and 1, with 1 being the maximum contrast. For a commercial AR system, the value of the MTF at 40 cycles/mm should be greater than 0.3 for an acceptably low distortion.[8] Below this threshold, it may become more difficult or even impossible to distinguish certain spatial frequencies.

Previous works have studied the maximum roughness a surface can reach before a single reflection degrades the MTF to an unacceptable level.[9] However, not enough work has been done to study the behavior of the MTF passing through a waveguide with more realistic surface roughness or with multiple reflections. It is important to see how certain characteristics affect the maximum resolution of the system: surface roughness, number of reflections, and refractive index. The effects of small-scale surface roughness on the MTF of a simulated AR waveguide are quantified. As an image is transmitted through an optical system, the magnitude of the MTF is degraded. Each non-ideal component of the system will affect the overall quality of the

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image. For instance, during TIR, imperfections in the surface finish of a waveguide can cause light to be reflected at non-ideal angles, blurring the final image. When light interacts with these rough surfaces once, the effect may not be significant; however, an image in a waveguide may be reflected dozens of times. In these scenarios the exact magnitude of surface roughness can play a significant factor in the maximum final image quality of the optical system.

Rough Surface Generation: Every optical surface will have a surface roughness that can be most readily described with a Gaussian distribution.[10] So, a 2D Gaussian rough surface was generated using the Monte Carlo Method.[9, 11] The primary statistical elements of concern with any rough surface are the root mean square (RMS) height (σ) and the correlation lengths (l_c). The RMS height describes the average deviation from a flat surface. For any given point, the height will on average differ from the ideal surface by the RMS height in either direction. The correlation length defines the distance over which the texture correlates with itself. First, the power spectrum of a Gaussian function is found using Equation 1.

$$W\left(K_x, K_y\right) = \frac{\sigma^2 l_x l_y}{4\pi} \exp\left(\frac{-\left({K_x}^2 {l_c}^2 + {K_y}^2 {l_c}^2\right)}{4}\right) \qquad (1)$$

Then, the height of the surface at the position (x,y) is then given by Equation 2.

$$h(x, y) = \frac{1}{L_x L_y} \sum_{m=\frac{M}{2}+1}^{M/2} \sum_{n=-\frac{N}{2}+1}^{N/2} F(K_m, K_n) \exp\left(i(K_m x + K_n y)\right) \qquad (2)$$

Where $F(K_m,K_n)$ can be found using Eq, (3):

$$F(K_m, K_n) = 2\pi \left(L_x L_y W\left(K_x, K_y\right)\right)^{\frac{1}{2}} * \begin{cases} \frac{N(0,1)+iN(0,1)}{\sqrt{2}}, & m_k \neq 0 \; and \; n_k \neq 0 \\ N(0,1), & m_k = 0 \; and \; n_k = 0 \end{cases} \qquad (3)$$

where L_x and L_y are the length and width of the surface. The spatial frequencies at the position (x,y) are given by $K_x = 2\pi x/L$ and $K_y = 2\pi y/L$, and N(0,1) represents a random number from a normal distribution where the mean is 0 and the variance is 1.

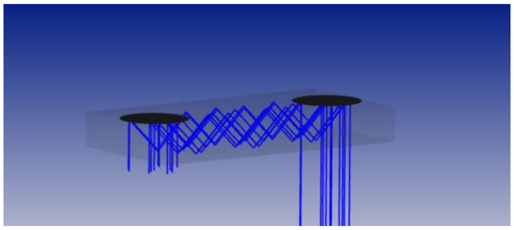

Figure 1. The 3D model of simulated waveguide for 5 total internal reflections

Simulation: A model waveguide was created in Zemax as seen in Figure 1. There are two ideal holograms that represent ideal couplers in a 1mm thick waveguide. Light is assumed to be perfectly collimated from the light engine source, and an ideal model of the human eye that has a focal length of 17 mm and a pupil size of 2 mm is placed after the output coupler with an eye relief of 15 mm. A randomly generated 2D Gaussian rough surface is imposed onto the surfaces of the waveguide where TIR occurs. The light is incident at an angle of 45 degrees. Several characteristics of a waveguide are investigated: RMS height, correlation length, the number of reflections, refractive index, and the wavelength. Previous studies have demonstrated that increasing the TIR angle of incidence reduces the degradation of the MTF.[9] So, the incident angle that would most clearly demonstrate the effects on the final resolution was chosen. Additionally, it was determined that the ratio between the correlation length and surface roughness was large enough such that a ray tracing simulation method was deemed to be a good approximation despite the RMS height being sub-wavelength.[11] The studied ranges of RMS height are orders of magnitude smaller than the correlation lengths studied.

2. Results

Surface Roughness: Exact values for the RMS height and the correlation length are not easily determined. They are often dependent on the manufacturing and treatment techniques used during their creation. Figure 2 shows a sudden drop in the MTF at 40 mm^{-1} after a single reflection as the RMS height increases. The standard waveguides all perform well, but even the small differences between them will compound as the image interacts with the waveguide multiple times.

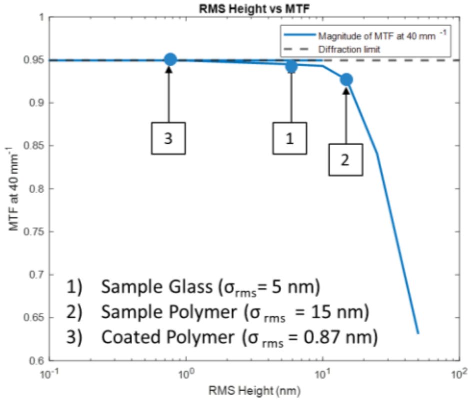

Figure 2. The magnitude of the MTF at 40 mm^{-1} after a single reflection vs the RMS height of the waveguide (l_c = 0.3 mm, n = 1.5, λ = 550 nm).

Correlation lengths are less commonly described when discussing surface roughness. It is used in discussions about generating rough surfaces, but it is often neglected when describing the specifications of commercial waveguides. Waveguides with the same RMs height but same correlation length can vary significantly. Figure 3 compares the MTF at 40 mm^{-1} after a single reflection as the correlation length is changed. As the correlation length increases and the RMS height decreases, the magnitude of the MTF increases exponentially until it reaches the diffraction limit, demonstrating the diminishing returns as the surface becomes increasingly smooth.

Number of Reflections: The number of reflections in a system is dependent on several different factors including the angle of incidence, the thickness, and the distance from the input coupler to the output coupler. The TIR angle is often limited by the critical angle. In many AR systems, other higher angles will propagate to create the full image. However, since we know shallower incident angles will result in greater scattering[9], the shallower angles will be neglected here to focus on the maximum potential risk to resolution loss.

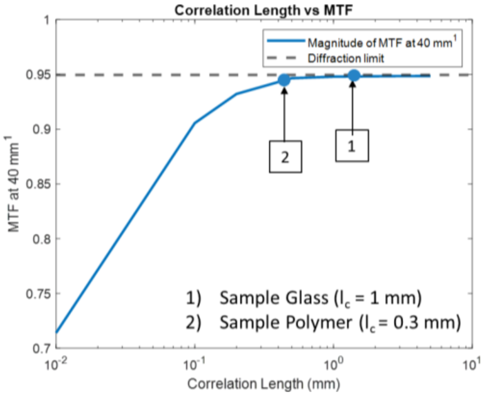

Figure 3. The magnitude of the MTF at 40 mm^{-1} after a single reflection vs the correlation length. A standard glass (1) and polymer (2) are labelled (σ_h = 5 nm λ=550 nm).

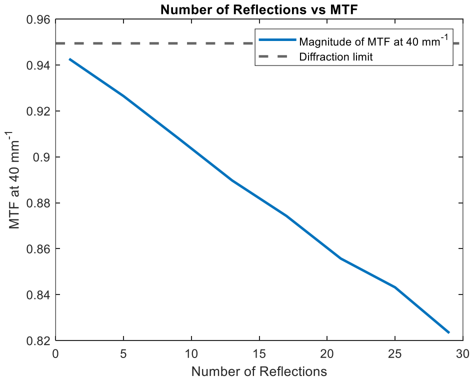

Figure 4. The magnitude of the MTF at 40 mm^{-1} after a single reflection vs the number of reflections from the rough surface. (σ_h = 5 nm = , n = 1.5, and λ = 550 nm).

For light at a 45° incident angle in a 1-mm thick waveguide, with 30 mm between the couplers, there are 29 total internal reflections. Naturally, as the number of reflections increases, a projected image will be scattered more and more each time. So, one must imagine that the MTF of the system will continually decrease as the number of reflections increases. To confirm this behavior and investigate its general behavior, multiple waveguides were simulated. Each time, only the length was changed. As seen in Figure 4, there was a steady decrease in MTF. For this simulated glass waveguide, there was not enough blurring to reach the previously defined threshold of 0.3. However, for rougher substrates, like those found in untreated polymers, the roughness can be enough to cause it to fall below threshold.

Wavelength: Higher index waveguides allow for an AR display to achieve a greater field of view, an attractive quality for many near-eye displays. Glasses tend to have notably higher refractive indices than plastic, which means that most glass waveguides have better potential for high FOVs. Although, high index polymers have been demonstrated with high index nanoparticles.[12] However, these may pose their own challenges due to additional absorption and scattering from the high index nanoparticles. As seen in Figure 5, as the refractive index increases, the MTF and 40 cycles/mm experiences a greater drop off. A higher refractive index means that light can reflect at higher incident angles. When light is incident on a groove at a higher angle, instead of refracting through, it is reflected back into the system, blurring the image. This may have a more significant impact on this simulation since the incoming light is close to the critical angle, so this occurs more often.

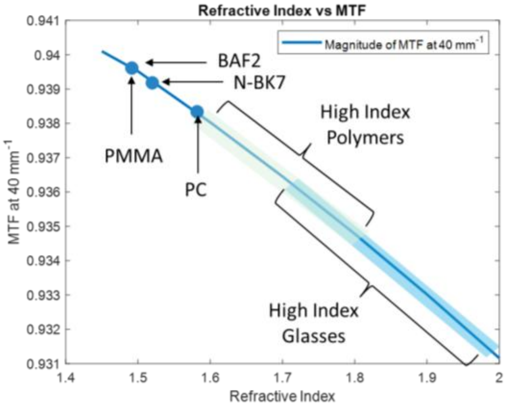

Figure 5. The magnitude of the MTF at 40 mm^{-1} after one reflection vs the refractive index (σ_h=5nm, l_c = 0.3 mm, λ =550 nm). Indexes of some common materials are labeled.

The sensitivity to the wavelength was also tested, and a behavior that mirrored the refractive index emerged. As the wavelength increased, the MTF at 40 mm^{-1} increased until it hit the diffraction limit.. However, as the wavelength increases, the effective refractive index decreases, and the lower critical angle means that less stray light will propagate in the system.

Image Simulation: A sample image was used to demonstrate the effects of this drop in MTF. Figure 7a shows the original image for the system before it was passed through 30 mm long waveguides with rough surfaces resembling that of glass (b), polymer (c), and coated polymers (d). For this test, the refractive index for each of them was kept constant at n = 1.6 to emphasize the effects of surface roughness. Upon inspection of these images, the untreated polymer waveguide sees the largest noticeable drop in image quality. Glass waveguides and coated polymers appear to retain much of the initial image quality, with only a few imperfections and a slight drop in brightness.

3. Discussion

Each waveguide variable was tested individually, when comparing attributes associated with each type of waveguide, particularly those associated with surface roughness, glasses had performance unless the polymer is treated with some secondary process or coating. For high resolution systems, untreated polymer waveguides may pose a threat to image quality. Strikingly, it appears that the waveguide characteristics that contribute to higher FOV appear to degrade image quality. A higher refractive index, shallower TIR angle, and more reflections from the shallow angle all lower the MTF, but these are done to increase the FOV in AR waveguides.[13] The roughness of the waveguide can become a bottleneck in higher FOV systems.

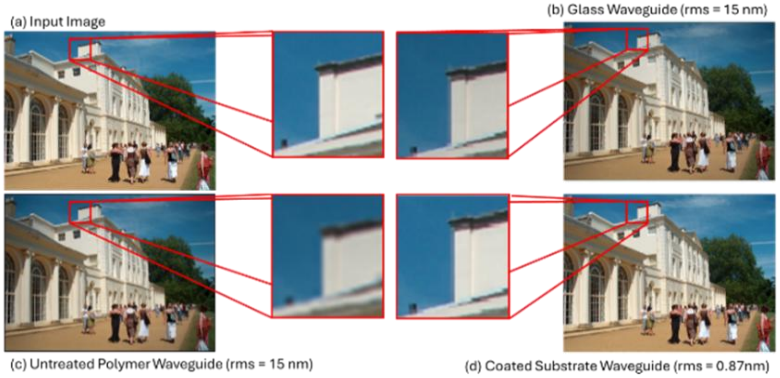

Figure 7. A sample image(a) and the image after passing through a (b) glass waveguide (σ=5 nm), (c) a polymer waveguide (σ=15 nm) and (d) a coated polymer waveguide (σ=0.87 nm).

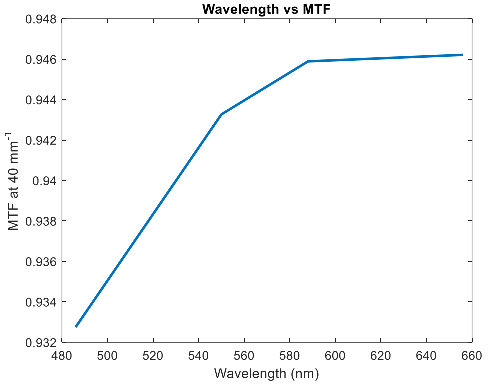

Figure 6. The magnitude of the MTF at 40 mm^{-1} after one reflection vs the wavelength (σ_h=5 nm, l_c = 0.3 mm, and n = 1.5).

4. Conclusion

As the industry strives for higher quality images, time and resources are rightfully spent focusing on making the light engine the highest resolution possible or on making the input and output couplers more efficient. One must not take the parts around it for granted. Ultimately, it is important for researchers and manufacturers to test the quality of their waveguides, for it can drastically impact the final image. If polymer waveguides are to be used for high resolution displays, it should be treated to guarantee that the images being generated can reach the human eye at the maximum resolution. Waveguides are one part of a complex and interconnected system. As the surrounding technologies continue to improve, one must ensure that the waveguides are of acceptable quality, so they are not the unexpected limiting factor for the system.

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