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Comparisons of glass and plastic waveguides for augmented reality glasses

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Abstract: Augmented reality (AR) waveguides are often treated as perfectly flat, but some degree of roughness present will blur the final image. By comparing the optical system's modulation transfer function (MTF), we find that glass waveguides with smoother surfaces can transmit higher resolutions than the untreated plastic waveguides with rougher surfaces. However, the coated plastic waveguides, achieved by spin-coating acrylic resin material to the plastic surface, can significantly reduce the roughness and attain surface quality comparable to that of glass. Additionally, we find that changing factors that widen the field of view such as refractive index and incident angle will make the system more sensitive to surface roughness.

1. Introduction

Augmented reality (AR) glasses [1,2], emerging as the platform for metaverse, digital twins, spatial computing, education, healthcare, and engineering, empower users to perceive digital images overlaid with real-world environment. With the rapid advances of input and output couplers, waveguide-based AR glasses have streamlined the entire system, boasting a stylish compact form factor, lightweight, and high optical performance [3,4]. Meanwhile, artificial intelligence (AI) makes AR glasses smarter and more powerful in areas like real-time language translations, global positioning system, upscaled image resolution, color temperature, adaptive frame rate control, and ambient contrast ratio, just to name a few. To facilitate all-day comfortable wearing, AR glasses must have a compact formfactor and lightweight, while keeping a sufficiently high ambient contrast ratio especially under outdoor sunlight conditions, and low power consumption to sustain a long battery operation life.

In waveguide-based AR glasses, the emitted light from a microdisplay panel is coupled into waveguide by an input coupler (such as surface relief gratings (SRGs) or polarization volume gratings (PVGs)), propagating along the waveguide via total internal reflection (TIR), and finally outcoupled by an output coupler (SRGs, PVGs or partial reflectors), and then projected to the user's eye [2]. Nearly all simulations and resolution calculations assume that these waveguides are perfectly smooth. However, no material can be perfectly smooth, and there will always be some deviation from an ideal surface. These deviations can vary greatly depending on both the material of the waveguide chosen, and how they are processed after shaping.

Most AR glasses use glass waveguides because of their sturdiness and high index, which enables a large field of view (FOV). In recent years, Cellid [5] and Magic Leap [6] have developed waveguides based on polymers rather than glass. Polymers are generally lower cost, more than 50% lighter weight, and provide additional malleability that can help create curved waveguides with optical power to compensate those users who need eyesight corrections [6]. 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, with the goal being a display that can match the human visual limit of 60 pixels per degree [7]. As the resolution of AR light engines continues to increase, it may be possible for the surface roughness of these waveguides to

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significantly reduce the image quality, less so than for many glass waveguides. Simultaneously, there is also a push for wider FOV systems, but there can be some consequences for the resolution by doing so.

In this paper, we compare the performances of glass and plastic waveguides by evaluating the optical system's modulation transfer function (MTF). We find that glass waveguides with smoother surfaces can transmit higher resolutions than conventional plastic waveguides, which are often rougher and harder to polish. However, the coated plastic waveguides, achieved by spin-coating acrylic resin material to the plastic surface, can significantly reduce the roughness and attain surface quality comparable to that of glass. Additionally, we find that changing factors that widen the FOV such as refractive index and steeper incident angle, i.e., angles closer to normal incidence, will make the system more sensitive to surface roughness.

2. Comparisons between glass and plastic waveguides

In the following, we will simulate the performance of glass waveguides and plastic waveguides in terms of surface roughness, MTF, and image degradation.

2.1. Surface roughness

In many forms of AR eyeglasses, the emitted light from a microdisplay is coupled into waveguide by an input coupler. It travels through the waveguide via TIR until it hits the output coupler. Both glass and polymers have been used as waveguide materials. However, no glass or plastic surface is perfectly flat, and microdefects in the waveguide can scatter light which blurs the final image. Normally, this effect may not be noticeable with lower resolution displays, or in thick waveguides with few reflections. As industry strives for AR devices with higher resolutions, something as simple as the roughness of the waveguide can blur the image so much that it is impossible to reach the human visual limit of 60 pixels per degree, even with a high-quality glass.

There are different scales to consider when discussing surface imperfections. Mid and low frequency surface deviations that contribute to the warp of a waveguide (sometimes called waviness) can pose significant issues. However, these deviations from an ideal surface are often well accounted for and easier to spot in optical quality waveguides, so they are not made a significant focus in this paper. They can be measured simply using interferometry [8]. The small scale, high frequency surface roughness is a factor that may be briefly mentioned, but not always. Despite this, they are still a major contributor to surface scattering [9]. These types of surface deviations often require more complex measurement methods such as atomic force microscopes or scanning electron microscopes [10]. In a well-polished surface, the typical values for root mean square (RMS) height of a surface may not produce significant aberrations for most optical systems. In lenses or other devices where an image may only interact with the surface one time, the aberrations caused by these tiny variations are often insignificant. While they are often ignored, in the specific application of 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 even the smallest imperfections can have on the final image quality of these systems.

The surface roughness of both polymer and glass waveguides can vary significantly, but in general, glass tends to be smoother than plastic. There are a variety of reasons for this. Glass has a more packed molecular structure compared to plastic's long, often disordered molecular chains. Additionally, plastic, being a softer, more easily warped material, is often more difficult to polish with conventional methods due to the risk of surface scratches and deformation. Although it is possible for polymer waveguides to achieve surface roughness similar to that of a higher end glass waveguide, it requires extra steps in the manufacturing process such as spin coating. Even so, some of these may be more difficult to achieve for waveguides that are not perfectly flat, and their hardness and strength may be considered for long term performance.

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2.2. Modulation transfer function (MTF)

The MTF describes how the amplitude of certain spatial frequencies changes as they pass through an optical system. Generally, the MTF of a system can be obtained via the Fourier transform of the point spread function (PSF), which describes the final image of a point source passing through the system. As with many simple lens systems, the human eye can pass lower frequencies to the retina, and the contrast at higher spatial frequencies gradually tapers off. 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 [11]. Below this threshold, it may become more difficult or even impossible to distinguish certain spatial frequencies. Assuming the focal length of the eye is 17 mm, this is equivalent to around 12 cycles per degree. Even though the angular resolution for our acceptable quality measure is lower than the human limit of 30 cycles per degree (or 60 pixels per degree), it is difficult to ascertain the exact extent to which a person can "see" a given contrast at a certain spatial resolution with the MTF alone. So, the authors deemed it acceptable to use previously found quality measures as the point of reference, and it is the number that will be used in further discussions. It should be noted that just because the MTF is lower does not mean that a person cannot see those frequencies. They may still appear as recognizable patterns, but the contrast at those frequencies is lower and may be harder to see as the MTF continues to decrease.

Previous works have studied the maximum roughness a surface can reach before a single reflection degrades the MTF to an unacceptable level [12]. 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.

For this investigation, 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 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.

In this waveguide system, after light passes through a model waveguide, the image passes through a model of the human eye (focal length of 17 mm, and a pupil diameter of 2 mm, which can vary from 2 mm to 8 mm depending on the ambient light brightness). In an optical system with a well-defined aperture like this, the MTF will have a diffraction limit that is related to the normalized Fourier transform of the aperture (the pupil). One notable behavior of the MTF is that if one knows the MTF of two systems, they can be multiplied together to find the total MTF of both systems in series. Future work could take advantage of this methodology to create a streamlined method of simulating the image quality of an entire AR optical system if the MTF of each individual component, and the effects of propagation are known.

2.3. Rough surface generation

Every optical surface will have a random surface roughness that can be most readily described with a Gaussian distribution [13]. So, a two-dimensional (2D) Gaussian rough surface was generated using the Monte Carlo Method [12,14]. The primary statistical elements of concern with any rough surface are the RMS height (σ) and the correlation lengths (l_c) in each direction. It is assumed that the correlation length is the same in both directions. The RMS height describes the average derivation from a flat plane. The correlation length defines the distance over which

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the texture correlates with itself, determining the scale over which the surface roughness is spread.

First, the power spectrum of a Gaussian function is found using

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

Then, the height of the surface at the position (x,y) is given by

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

where the F(K_m,K_n) can be found using Eq. (3):

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

where L_x and L_y are the lengths and widths 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.

2.4. Simulation

A model waveguide was created in OpticStudio as shown in Fig. 1. There are two ideal mirror holograms that represent ideal input/output couplers for a 1-mm thick waveguide. A perfect mirror-like holographic input and output coupler was used. Both diffractive and refractive coupling methods are common, and they can all have their own unique impact on the MTF. In some instances, pupil clipping can occur as the image interacts with SRG and metasurface couplers multiple times before being projected to the eye [15]. Other PVG coupling methods do not experience this clipping [16]. Since the primary focus of this study is on how the surface profile of the waveguide affects the image quality, the input and output couplers are assumed to be ideal for the wavelengths studied without concerns about how a specific coupling method may impact the image quality. Further research could investigate the extent to which the choice of input and output couplers changes the final MTF.

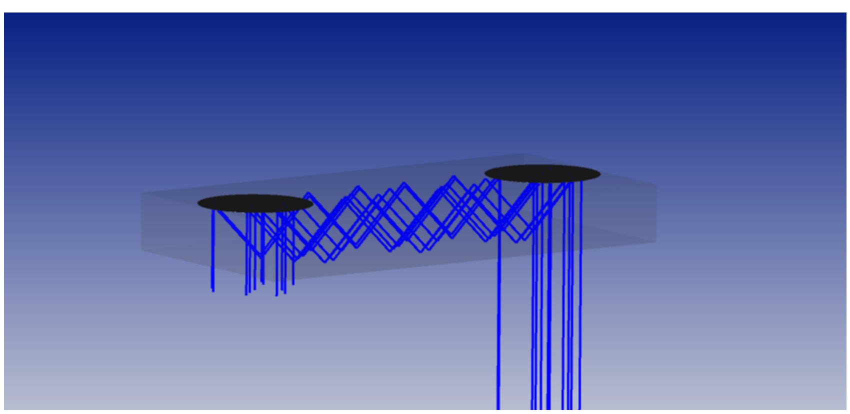

Fig. 1. The 3D model of simulated waveguide for 5 total internal reflections.

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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 top and bottom surfaces of the waveguide where TIR occurs. The light is assumed to be incident at an angle of 45 degrees, close to the critical angle of the material investigated. Several different characteristics of a flat waveguide are investigated: RMS height and correlation length of the surface roughness as well as other factors like 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 [12]. So, the steeper incident angle that would most clearly demonstrate the effects on the final resolution was chosen.

The surface roughness parameters under investigation are often smaller than the wavelength, raising questions about the validity of a geometrical optic analysis of this behavior. However, even though the RMS height of the roughness is smaller than the wavelength of light being investigated, the ratio of the RMS height to correlation length was determined to be long enough to ensure that raytracing is still valid [14]. Here, where the correlation length can be orders of magnitude more than the RMS height, rate of change of the surface means that the wave properties of light are less significant, and it will still act mostly like a ray. This means that a raytracing approximation can be used to provide a good estimate of the behavior of an image passing through the system. It is known that small surface roughness can drastically affect scattering of light while propagating [9]. This assumption allows for reasonable estimates of image propagation behavior even for large systems that would typically be too computationally demanding to simulate using wave mechanics.

3. Results

3.1. Surface roughness

Exact values for the RMS height and the correlation length are not easily determined. They are often dependent on the manufacturing, polishing, and treatment techniques used during their creation. The primary surface roughness characteristics being investigated are the RMS height and the correlation length. For each test, the refractive index and target wavelength were kept constant, even though different materials will have unique values, to determine exactly how much each variable could affect the image quality. Typical values of different materials are labelled. These can provide insight into how much either variable may affect the final image quality.

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. Figure 2 shows a sudden drop in the MTF at 40 mm^{-1} after a single reflection as the RMS height increases. The standard values for RMS height in waveguides all result in good performance, but even the seemingly small differences between them will compound as the image interacts with the waveguide multiple times.

Correlation length tends to be less commonly described when discussing surface roughness, but it remains an important factor. Often, it is used in discussions about generating rough surfaces, but characteristics like this that define the rate of change in small scale roughness are often neglected when describing the characteristics of commercial waveguides. As the correlation length increases, the height across the surface changes less rapidly, meaning this characteristic remains an important characteristic of any waveguide. Surfaces with the same RMS height can give very different scattering behaviors if the correlation length is changed. With this in mind, the extent to which the correlation length affects the MTF of the system are examined. Figure 3 contains a plot comparing the MTF at 40 cycles/mm after a single reflection in a glass substrate for correlation lengths between 0.01 mm and 4 mm. The correlation length of a polymer may reach as low as 1.79 mm [17], but this reaches the limits of the geometric raytracing approximation.

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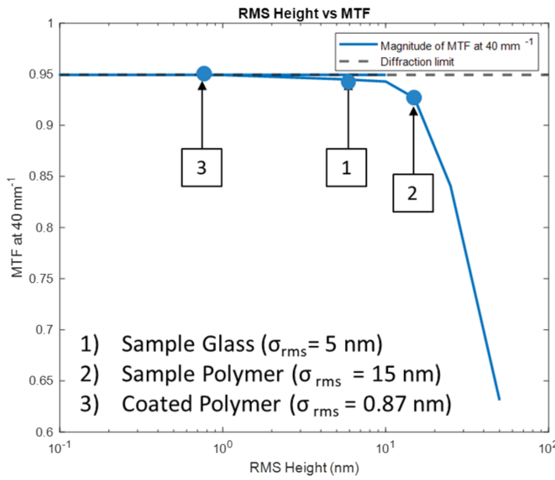

Fig. 2. The magnitude of the MTF at 40 mm^{-1} (12 cycles per degree) after a single reflection vs the RMS height of the waveguide (l_c = 1 mm, n = 1.5, λ = 550 nm). A standard glass (1), polymer (2), and coated polymer (3) are labelled.

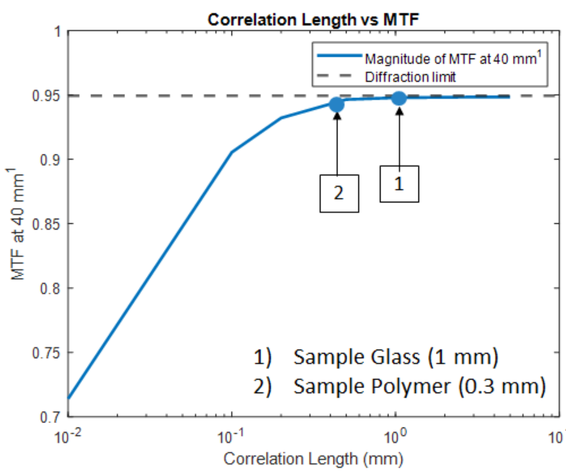

Fig. 3. The magnitude of the MTF at 40 mm^{-1} (12 cycles per degree) after a single reflection vs. the correlation length. A standard glass (1) and polymer (2) (σ_h = 5 nm, n = 1.5, and λ = 550 nm).

There is a logarithmic relationship between the correlation length and the MTF height. 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.

3.2. Number of reflections

The number of reflections in a system is dependent on several different factors including the angle of incidence, the waveguide thickness, and the distance from the input coupler to the output coupler. For any given incident angle θ propagating in the waveguide, the approximate maximum

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number of reflections, N, can be found using following equation:

$$N = \frac{L}{\mathrm{dtan}(\theta)} - 1, \tag{4}$$

where d is the waveguide thickness and L is the distance between the input and output couplers. The reflections from the input and output couplers here are ignored. Multiple different coupling methods exist, and they will have their own unique effects on the final resolution, which is not the focus of this investigation.

The maximum number of reflections for a source propagating through a waveguide is defined by the TIR critical angle. In many AR systems, other shallower angles will propagate to create the full image. However, since it has been demonstrated that steeper incident angles will result in greater scattering [12]. So, as the incident light becomes closer to normal incidence, we expect the MTF degradation to increase. For this reason, shallower angles will be neglected here to focus on the maximum potential risk to resolution loss.

For light at a 45° incident angle in a 1-mm thick waveguide, with 30 mm between the input and output couplers, there are as many as 29 total internal reflections. As industry pushes for thinner waveguides, the number of reflections rapidly increases according to Eq. (4). 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 Fig. 4, there is 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.

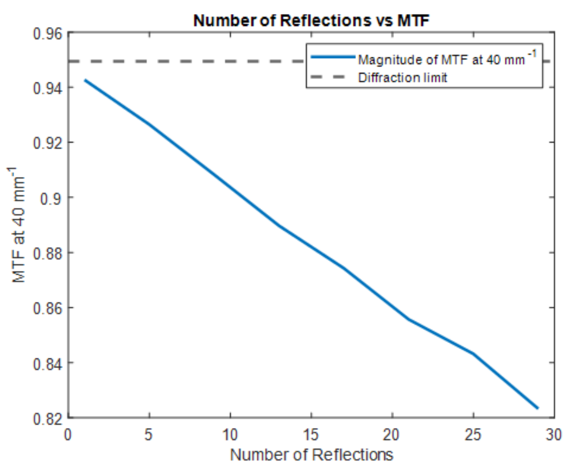

Fig. 4. The magnitude of the MTF at 40 mm^{-1} (12 cycles per degree) after a single reflection vs the number of reflections from the rough surface. ($\sigma_h = 5$ nm, $l_c = 1$ mm, n = 1.5, and $\lambda = 550$ nm).

3.3. Effects of refractive index and wavelength

Higher index waveguides allow for an AR display to achieve a wider FOV, 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. High index polymers have been demonstrated by either introducing substituents with high molar refractions or by doping

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high-index nanoparticles to the polymer matrixes [18]. However, these high-index polymers may pose their own challenges due to additional absorption and scattering from the nanoparticles.

As Fig. 5 shows, as the refractive index increases, the MTF at 40 cycles/mm experiences a greater drop off. This is likely because a higher refractive index means that the TIR critical angle is lower. So, a beam at a steeper (closer to normal) angle of incidence can still propagate. Within the waveguide, when the light is incident on a groove at a steeper angle, instead of refracting through, it is more likely to be reflected into the system. This additional light off the correct path would blur the final image more than if it had exited the system. This effect may have a more significant impact on this system since the simulation has incoming light at an incident angle close to the critical angle, so this may occur more often.

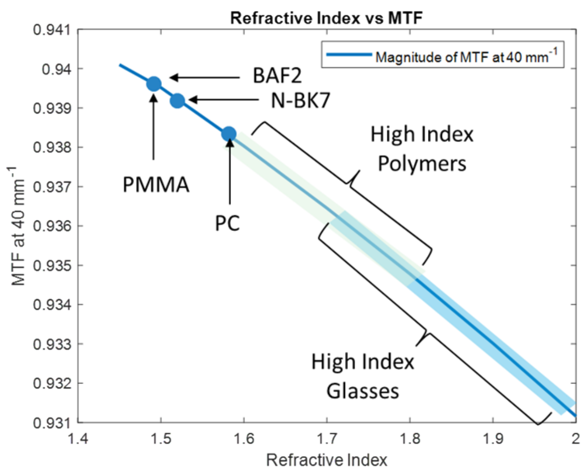

Fig. 5. The magnitude of the MTF at 40 mm^{-1} (12 cycles per degree) after one reflection vs the refractive index ($\sigma_h = 5$ nm, $l_c = 0.3$ mm, $\lambda = 550$ nm). The refractive index of some common materials is labeled.

This effect may result in a slightly brighter image in some scenarios since more light can be kept within the waveguide. However, it should be noted that the MTF is not simply a measure of brightness; it is a measure of contrast at different spatial frequencies. A brighter image does not necessarily mean the MTF is higher. If a ray of light is not reflected at the correct angle, it will blur the final image, making it more difficult to distinguish higher spatial frequencies. Having a higher critical angle means that rays that some off-axis rays that could have been ejected from the system are more likely to propagate through the waveguide. This lowers the maximum potential contrast for higher frequencies, reducing the MTF. One could also consider how these off-axis rays will result in a wider point spread function (PSF). Since the MTF can be seen as the Fourier transform of the PSF, a wider PSF means a narrower MTF, consistent with the observations from the simulation.

The sensitivity to the wavelength was also tested, and a behavior that mirrored the refractive index emerged. As the wavelength increases, the magnitude of the MTF appears to increase until it approaches the diffraction limit, as Fig. 6 depicts. This is a bit counterintuitive since generally the MTF of a system will decrease as the wavelength increases. This is because the MTF is diffraction limited, and since a longer wavelength diffracts more so that it exhibits a lower MTF. However, when observing the issue to a similar lens used when the refractive index is discussed, this effect becomes reasonable. As the wavelength increases, the effective refractive index decreases, and the lower critical angle means that less light that is off the ideal path will stay within the system. The exact extent of these effects may be blurred by the choice to use a

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raytracing approximation rather than a wave-based approach, and further work can be done to test the exact accuracy of either method.

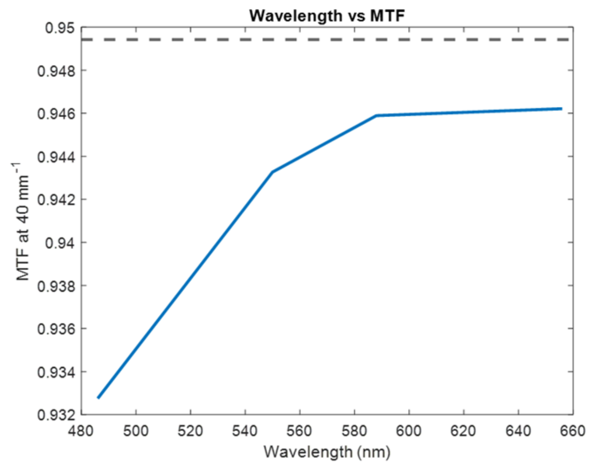

Fig. 6. The magnitude of the MTF at 40 mm^{-1} (12 cycles per degree) after one reflection vs. the wavelength ($\sigma_h = 5$ nm, $l_c = 0.3$ mm, and $n = 1.5$).

3.4. Field of view and image simulation

Previous works have shown that the MTF sees a lower degradation for beams at shallower incident angles [12]. So far, the effects on the MTF have been studied for collimated beams at steep angles near the critical angle of the waveguide, where one would expect the MTF degradation to be the worst. However, in AR waveguides, shallower angles will also propagate. If light from an image source is collimated before entering a waveguide, then each point in the image will result in beams of light with different propagation angles. The steepest of these angles is the critical angle, and the upper limit of the reflecting angles is determined by that which gives too large of a gap between consecutive reflections such that it decreases uniformity. [19] The TIR angle of collimated light from a pixel on a display changes depending on its location. As one moves across the image source, the internal reflection angle of a collimated pixel's beam will change. In Fig. 7, the 0-degree angle corresponds to the light coming from the center of the image. This will have a TIR angle that is halfway between the maximum and minimum values. In this simulation, an off-axis beam angle of -15^{o} corresponds to the collimated pixel beam whose TIR angle is closest to the angle of incidence. The $+15^{o}$ beam has the largest TIR angle inside of the waveguide.

For each waveguide, four random surfaces were generated, and the average value of the MTF at each angle was recorded. As Fig. 7 shows, for every type of waveguide, the steeper the TIR angle for a collimated pixel beam is, the less the MTF degrades. This implies that larger angles of incidence further from the critical angle are more resistant to rough surface scattering.

Following this, a sample image was passed through each waveguide to demonstrate the effects of the calculated drop in MTF. As shown in Fig. 7, a glass and coated polymer waveguide should offer similar performance, whereas a polymer waveguide should see a much lower quality image. Figure 8(a) shows the original image for the system. The test image was simulated to pass through three different 30-mm long waveguides with rough surfaces resembling glass (Fig. 8(b)), polymer (Fig. 8(c)), and resin coated polymers (Fig. 8(d)). For this test, the refractive index for each of them was kept constant at $n = 1.5$ to only focus on the effects of surface roughness. Upon inspection of these images, the untreated polymer waveguide experiences the largest noticeable

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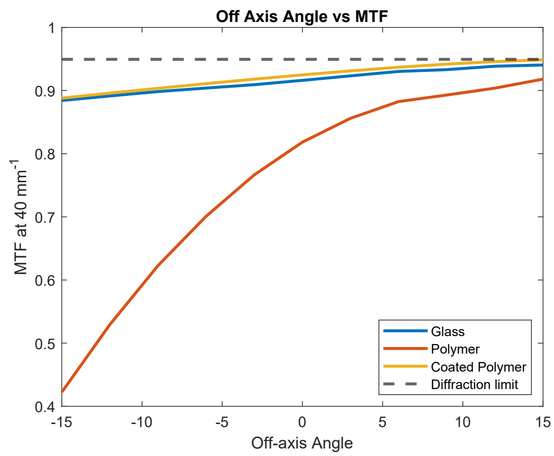

Fig. 7. The magnitude of the MTF at 40 mm^{-1} (12 cycles per degree) after passing through a 30 mm long waveguide made of glass ($\sigma_h = 5$ nm), polymer ($\sigma_h = 15$ nm) and coated polymer ($\sigma_h = 0.87$ nm) versus the off-axis angle of a collimated pixel beam ($n = 1.5$, $\lambda = 550$ nm).

drop in image quality. Glass waveguides and coated polymers appear to retain most of the initial image quality, with only a few imperfections and a slight drop in brightness.

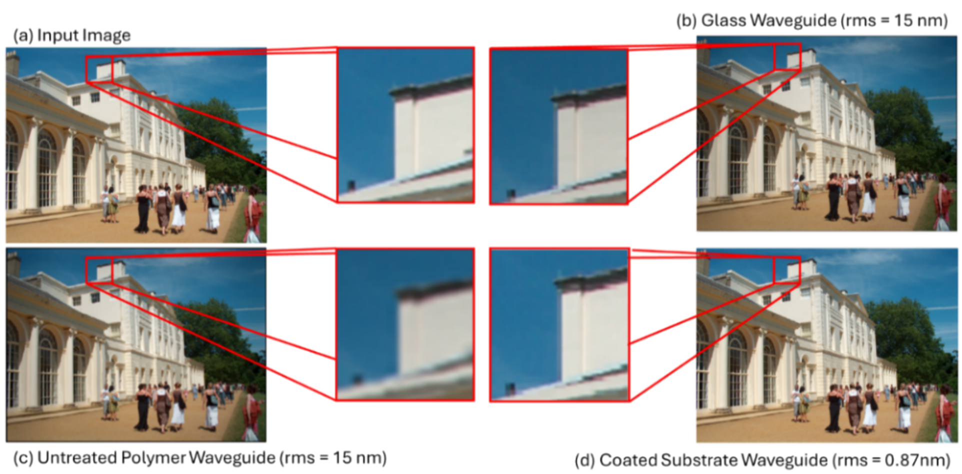

Fig. 8. (a) A sample image and the simulated image after passing through a (b) glass waveguide ($\sigma = 5$ nm), (c) an untreated polymer waveguide ($\sigma = 15$ nm), and (d) an acrylic resin coated polymer waveguide ($\sigma = 0.87$ nm). FOV is $\pm 15°$. Initial image resolution is 640×480.

4. Discussion

The final image quality of any given waveguide composition will always be constrained by the diffraction limit. Though each variable for a waveguide was tested individually, when comparing attributes associated with each type of waveguide, particularly those associated with surface roughness, glasses tend to lead to better performance unless the polymer is treated with some secondary process or coating. Plastic waveguides have recently been favored in some commercial headsets due to their lower cost and shatter resistance. While it is possible for them to achieve

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higher index and better smoothness, these attributes are more difficult to achieve compared to their glass counterparts. So, for ultrahigh resolution systems, untreated polymer waveguides may pose a significant threat to image quality. Glass waveguides on the other hand, while more expensive and heavier, can more simply achieve a smoother surface. Additionally, glass waveguides may have the potential for a higher FOV due to their higher refractive index. Polymers have achieved high indexes rivaling glasses, but the methods used to achieve this could introduce additional scattering losses, reducing the image quality further.

Increasing the refractive index appears to degrade the MTF more than the same percentage increase in RMS height. However, there is far more variability in the RMS height between materials than in the refractive index, and the RMS height of a waveguide can be changed far more easily via polishing, whereas the refractive index for a material is constant.

The most important risks to the image quality degradation appear to be factors relating to the surface roughness: RMS height and correlation length. These have the largest amount of variation among waveguides when compared to other factors like the refractive index, which are often fixed quantities. Strikingly, it appears that many of the relatively fixed waveguide characteristics that contribute to higher FOV appear to degrade image quality. A higher refractive index, shallower angle of incidence, and more TIRs from the shallow incident angle will all result in a lower MTF, but these are also the things that are traditionally done to increase the FOV for these AR systems [19]. This highlights an important tradeoff between FOV and image resolution. Even seemingly small increases in the surface roughness of a waveguide can have compounding effects, limiting the maximum possible resolution of larger FOV systems. It appears that to maintain high resolution in large FOV systems, the quality of the waveguide can become a bottleneck.

5. Conclusion

As the augmented reality industry strives for projections that match the resolution of the human eye, a lot of time and resources are rightfully spent focusing on making the display light engine the highest resolution possible or on making the input and output couplers the most efficient. However, as these improvements are made, it is important not to take the systems around it for granted. Ultimately, it is important for researchers and manufacturers to thoroughly test their chosen waveguides, for it can have a drastic impact on the final image quality of their devices. If polymer waveguides are to be used for high resolution AR applications, it is recommended that they are properly treated via methods like spin coating to guarantee that the images being generated by such high-end image sources can reach the human eye at the maximum resolution. Waveguides are but one part of a complex and interconnected system. As the surrounding technologies continue to improve, it becomes increasingly important to ensure that the waveguides used are of high enough quality, so they do not become the unexpected limiting factor for the system.

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