Bio-inspired Subwavelength Nanostructures for Antireflection (AR)

Most optoelectronic devices, such as solar cells and consumer displays, require glass or plastic covers for protection against environmental stress. These protecting layers create optical reflections which can significantly reduce the device performance. Currently, the most common antireflection (AR) approach to minimize these reflections is to deposit optically interfering thin films. However, the optical properties of these thin-film coatings are strongly dependent on the wavelength, angle and polarization of the incident light, which greatly limits their antireflection performance. Edgehog's solution, bio-inspired antireflective nanotextures, is a highly scalable approach to drastically reduce reflections (<0.1%) on various substrates, over the entire visible and near-IR spectrum and even at large angles of incidence.

Background: Antireflection Approaches

When light is incident on a flat interface between different materials (Fig. 1a), the normal reflectance R created by the abrupt change in refractive index n is described by Fresnel's equation:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

For regular glass (n2 ≈ 1.5) surrounded by air (n1 = 1), the reflectance at normal incidence is about 4%, or 8% accounting for both sides of a glass pane.

To reduce these unwanted reflections, surfaces are often coated with an anti-reflective thin film, whose refractive index and thickness are chosen to cause destructive interference in the waves reflected at each interface (Fig. 1b). Since this approach relies on interference, it is optimized only for a single wavelength and a single incident light angle.

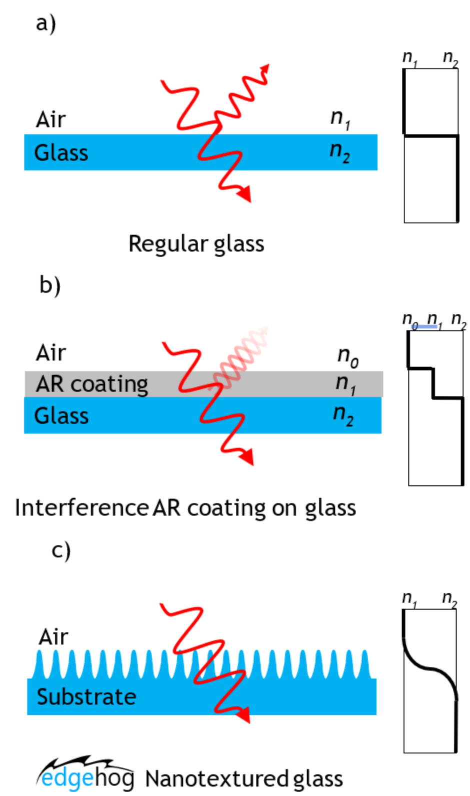


Fig. 1 a) Fresnel reflection at the interface between air and glass. b) Workings of a single-layer interference coating. c) Subwavelength nanostructures create a smooth gradient of refractive index that eliminates reflection.

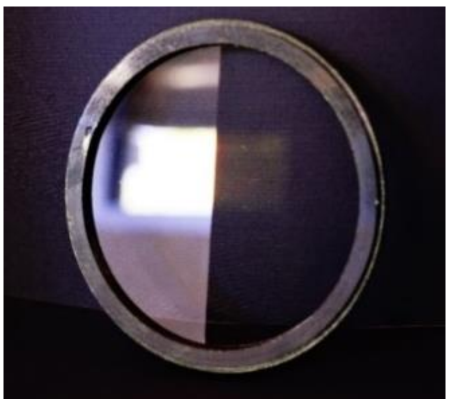
Edgehog Bio-inspired Nanostructure AR

A more powerful solution to reduce the reflectance is to eliminate the discontinuity at the interface altogether by gradually varying the refractive index between the two materials. Creating an effective refractive index with the desired spatial profile can be accomplished by appropriately texturing the surface at a scale smaller than the wavelength of light (Fig. 1c).

Antireflection Performance

Using nanostructures, Edgehog's technology can provide glass surfaces with 99.8% light transmission. Fig. 2a shows a circular glass with Edgehog's nanotextured surface applied to the right half of the glass. The photo is taken under an incandescent light source to compare the surface reflectance with the generic glass (the left half). The enhanced anti-reflectance of Edgehog's glass is clearly seen. Fig. 2b shows an example of a scanning electron microscope cross-section of the fabricated glass exhibiting etched structures.

a)



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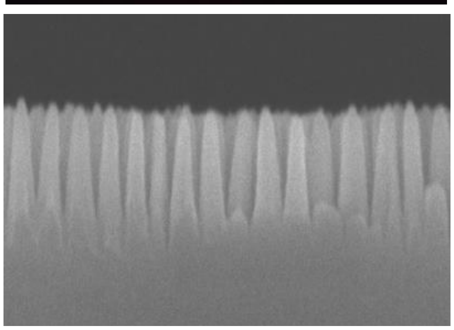

Fig. 2. a) Comparison of regular (left half) and nanotextured (right half) glass, illuminated by ambient lighting showing greatly reduced reflectance from the nanotextured sample. b) Cross-sectional view of the nanotextured surface with 200-nm-tall cones.

With the nanostructure approach, broad and flat transmission is observed throughout the visible spectrum and into the IR, resulting in low reflectance (Fig. 3). This makes Edgehog's technology exceptionally suitable for displays. Measured reflectance can reach as low as 0.1%, preventing the deterioration of contrast ratio typically observed under bright conditions. The antireflection effect derives from the gentle gradient of the index of refraction from air to the substrate. As such, the color of the reflectance stays neutral regardless of the viewing angle.

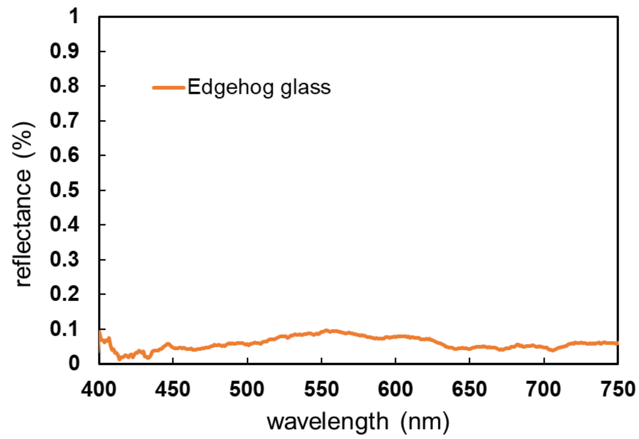

Fig. 3. Reflectance of Edgehog glass (fused silica GJS2) in visible spectrum is less than 0.1%.

Figure 4 shows the comparison of Edgehog glass with bare fused silica glass. The reflectance is decreases throughout the spectrum from 250 to 2500 nm. The low reflectance of <1% in the UV range makes the technology promising for a window glass for high power laser applications.

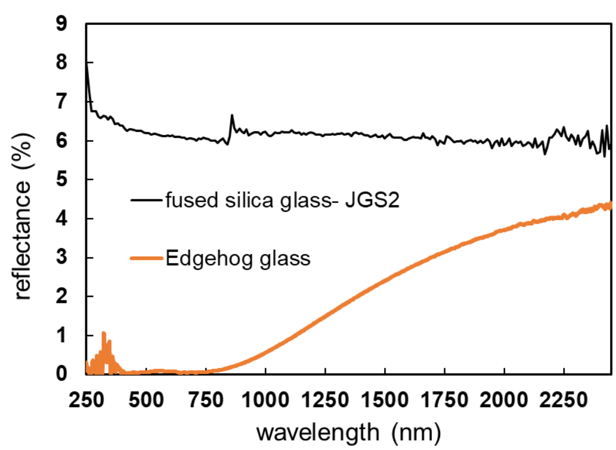

Fig. 4. Reflectance of Edgehog glass (fused silica GJS2) in wavelength range 250-2500 nm.

Thermal damage

Due to the near total transmission of light, nanostructured surfaces reduce thermal damage caused by concentrated light sources like high power lasers or concentrated solar applications. Fig. 5 shows that for our nanostructured windows, the optical fluence for damaging the front surface by laser is 59.59 J/cm^2 and 75.39 J/cm^2 for two variations of our nanostructure. This is an order of magnitude improvement over commercial AR thin-films, with 2-4 J/cm^2 values. Measurements were made using 5 ns laser pulses at 532 nm at repetition rate of 50 Hz.

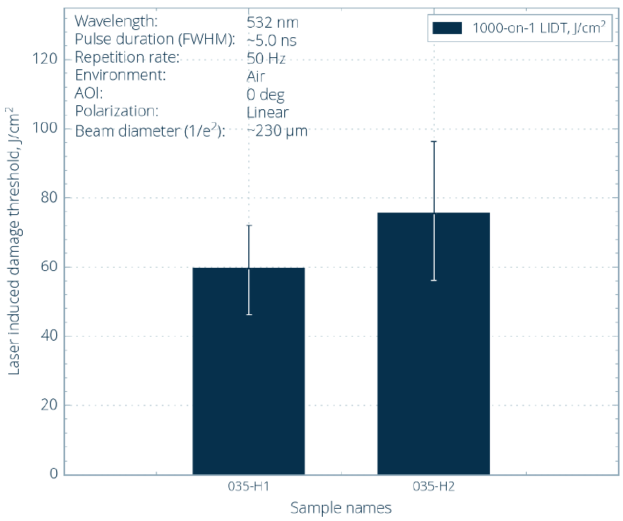

Fig. 5. Measurement of laser induced damage of nanotextured glass.

Conventional optical interference-based AR consists of multiple thin-films with different chemical composition. When exposed to temperature cycles in ambient conditions, layers expand and different rates and amplitude, resulting in flaking and peeling.

Because the Edgehog nanotextured glass is not a coating, but rather, is composed of native glass features, there is no chemical gradient, ensuring long-lasting functionalization in environmental conditions.

Angle Independence

As the viewing angle deviates from normal, not only does the transmissivity decrease dramatically (Fig. 6), but the profile of the reflectance spectrum also changes with the increased pathlength, resulting in "color shift" of the reflected light. Angle independence is a key property of nanotextured glass that is beneficial to solar panels since it can eliminate reflection losses due to large angles of incidence. In addition, this technology is suitable for displays designed to accommodate multiple simultaneous viewers as the content can be viewed from various angles without altering the visual properties.

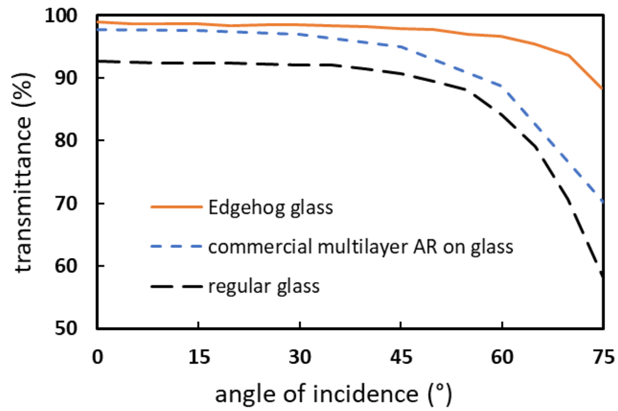

Fig. 6. Angle dependence characteristics for regular glass (black), multilayer interference films (orange), and nanotextured glass (blue).