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Wide-Angle Antireflection (AR) Coatings

A problem with all interference-dependent AR coatings is excessive reflection of light rays arriving at large angle of incidence - due mainly to the increased distance these rays travel in each coating layer. It can be mitigated somewhat in the coating design process, but excessive reflection occurs at angles of incidence greater than ~ 45 degrees. This causes unwanted reflections from eyeglasses and other lenses and serious efficiency loss in solar cells due to the high index of refraction of semiconductors.

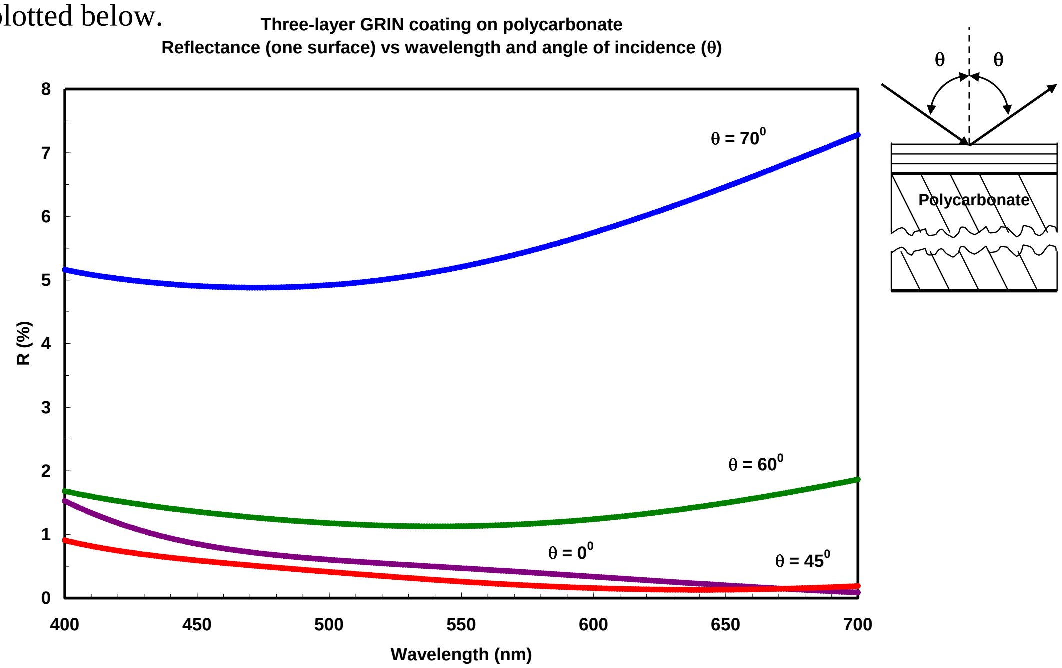
New developments are likely to make wide-angle, wide-bandwidth coatings practical. In theory [1], negligible reflection over a very wide range of angles and wavelengths can be achieved with a large number of thin layers, whose index of refraction decreases in small steps from that of the substrate to that of the medium (usually air, n=1.00). Since the lowest index available in solid materials is approximately 1.3, this requires coatings with microscopic voids.

Graded-index (GRIN) layers of such coatings can be deposited by minor modification of current vacuum-evaporation techniques [2]. I can help commercial coating labs make these modifications.

More recently, workers found that low reflection over a considerable wavelength and angle range can be achieved with as few as two, three, or four discrete layers, if the index step size and layer thicknesses are properly chosen [3,4]. This greatly reduces production cost. These coatings rely on a combination of wave interference and graded-index effects.

I designed a three-layer GRIN coating to minimize visible-light reflection from polycarbonate. It uses the same principles as the two-layer coating on glass described in reference [4], which was optimized for longer, infrared wavelengths. Calculated reflectance of unpolarized light from one surface is plotted below.

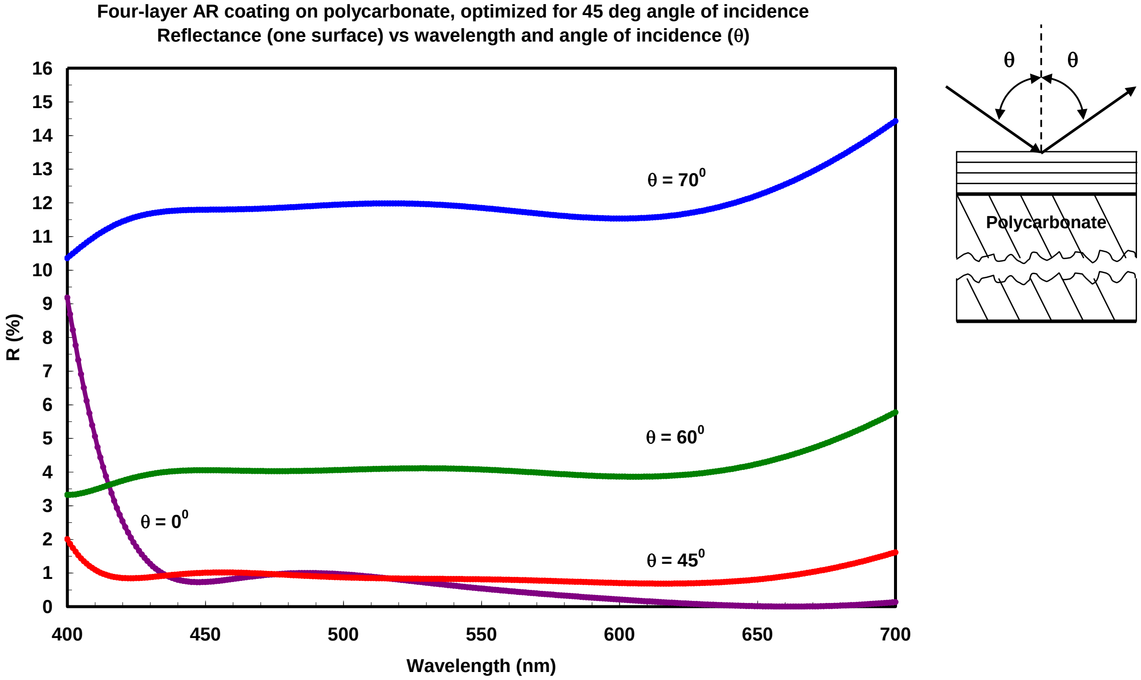
Three-layer GRIN coating on polycarbonate
Reflectance (one surface) vs wavelength and angle of incidence (θ)



Reflectance is reasonably low (< 2%) for angles of incidence up to 60 degrees. Even at 70 degrees, maximum reflectance is 7.4%, while reflectance of unpolarized light at this angle from uncoated polycarbonate is ~ 19%.

My coating layers, in order from polycarbonate to air, are non-porous silicon dioxide (n ~ 1.48), porous (13 volume % voids) silicon dioxide (n ~ 1.42), and porous (59 volume % voids) silicon dioxide (n ~ 1.20). Total coating thickness is 229 nm.

For comparison, I re-optimized my conventional four-layer Durable Anti-Reflection Coating for better performance at large angles of incidence. Calculated reflectance of unpolarized light from one surface is plotted below. Note that reflectance at 60- and 70-degree angles of incidence is nearly twice that of the GRIN coating.



I have some concern about porous, low-index GRIN coatings' abrasion resistance and their performance while wet. Thus the first practical applications may be on solar cells, where the potential efficiency improvement is large [3] and the cover glass will provide abrasion and moisture protection. And new developments, such as encapsulation of voids in a durable matrix [5], are likely to facilitate a wider range of applications.

[1] J. S. Rayleigh, *On reflection of vibrations at the confines of two media between which the transition is gradual*, Proceedings of the London Mathematical Society, Vol. 11, pp 51-56 (1879).

[2] Scott R. Kennedy and Michael J. Brett, *Porous broadband antireflection coating by glancing angle deposition*, Applied Optics, Vol. 22, No. 22, pp 4573-4579 (2003).

[3] Martin F. Schubert, David J. Poxson, Frank W. Mont, Jong Kyu Kim, and E. Fred Schubert, *Performance of antireflection coatings consisting of multiple discrete layers and comparison with continuously graded antireflection coatings*, Applied Physics Express, Vol. 3, 082502-1 – 082502-3 (2010).

[4] Sameer Chhajed, David J. Poxson, Xing Yan, Jaehee Cho, E. Fred Schubert, Roger E. Welser, Ashok K. Sood, and Jong Kyu Kim, *Nanostructured multilayer tailored-refractive-index coating for glass with broadband and omnidirectional characteristics*, Applied Physics Express, Vol. 4, 052503-1 – 052503-3 (2011).

[5] http://www.dsm.com/content/dam/dsm/cworld/en_US/documents/light-transmittance-enhancement-over-lifetime-performance-of-anti-reflective-pv-module-cover-glass.pdf