Humidity Controlled Tuning of Hybrid Distributed Bragg Reflectors (DBRs)

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Motivation

In 2018, the world consumed approximately 26,700 TWh of energy [1]. For perspective, 1 TWh is equivalent to 1 billion tons of coal. By 2050, this demand is expected to nearly double to over 42,000 TWh of energy [2]. With the continued rise in global temperatures and growth of developing countries, space cooling applications will grow to be a large part of this energy demand. It is expected that space cooling will take up 37% of our overall electricity demand by 2050. This is more than three times the current demand, which is equivalent to the combined energy capacity of the United States, Europe, and Japan today [3].

A way to mitigate this future energy demand for space cooling is to reduce energy consumption in buildings. This project focused on the development of a coating that with exposure to humidity would reject or transmit thermalizing infrared light or near-infrared wavelengths (~740 – 1400 nm) of the electromagnetic spectrum. This would allow control over the admission of radiative heat into a building, reducing the load upon HVAC systems. For future large scale applications, cheap, readily accessible materials and potentially scalable production processes were considered.

Background

For this coating, a stacked DBR structure was chosen to reflect near-infrared light at a designated wavelength or stopband. A DBR structure is composed of alternating layers of high and low refractive index materials, where the index of refraction is related to the speed of light through a medium. The high index layer consists of a hybrid of titanium hydrate and polyvinyl alcohol (PVAl), and the low index material is poly(methyl methacrylate) (PMMA), a commodity plastic.

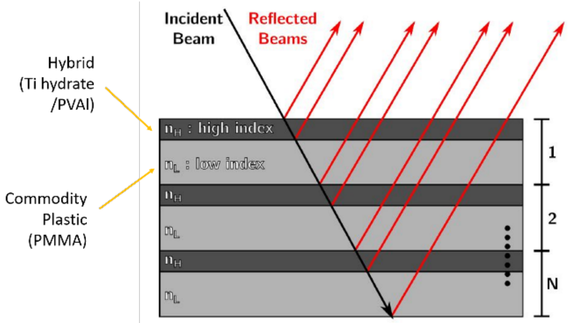

Figure 1, DBR Structure & Materials [4]

Methods

DBR Fabrication

DBR structured coatings were fabricated on glass and poly(propylene) substrates using the process of dip coating. Calibration curves for hybrid upon glass and PMMA upon hybrid were constructed by correlating thickness to dip speed. Profilometry tests were performed to obtain rough thickness checks of the layers. Transmittance data for the DBR structures were acquired using UV Visible Spectroscopy. The number of bilayers were increased to deepen the reflection of the stopband. Adjustments were also made to obtain more consistent film thicknesses. Good spectra periodicity was used to confirm thickness uniformity of the layers. Two DBR structures were considered to maximize reflection of near-infrared wavelengths. A dielectric mirror structure has layers of constant thickness, while a chirped structure consists of bilayers that increase or decrease in thickness. Ideally, a wider region of reflection can be obtained around the operating wavelength.

Swell Testing

The DBR coatings were annealed at 120°C to establish baseline spectra. This heat treatment converted remaining $TiCl_4$ to the titanium hydrate form as well as removed residual water and byproducts. The coatings were then exposed to approximately 100% humidity at a constant room temperature and subsequently re-dried at 45°C.

Results

With the dielectric mirror DBR structure, a stopband was successfully obtained in the near-infrared. Secondary and tertiary reflections were observed in the visible spectrum, indicating the good quality of the layers. The structure was adjusted to ensure reflection at the 1000 nm wavelength, and the tertiary reflection was shifted into the ultraviolet region.

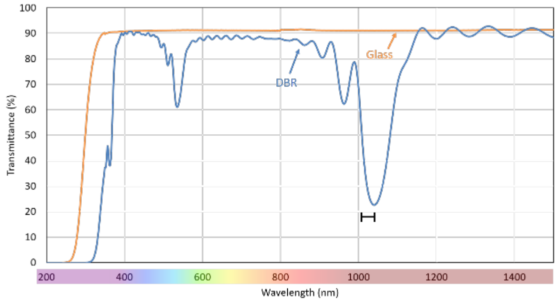

Figure 2, Spectra for Tuned Dielectric Mirror DBR Structure upon Glass

Exposure of the chirped DBR structure to humidity resulted in a considerable reduction of the stopband, allowing significant transmittance in the near-infrared. With re-drying, the spectra was returned closely to that of the annealed (baseline) sample, with the coating again reflecting the near-infrared.

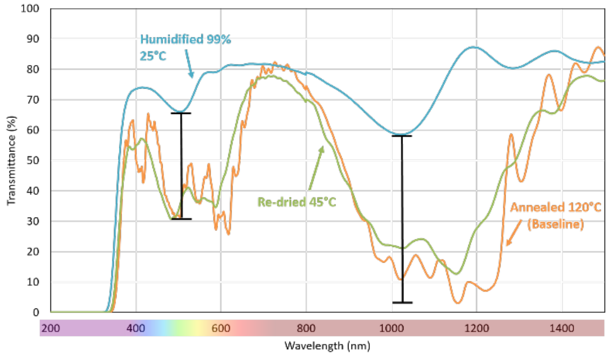

Figure 3, Spectra for Chirped DBR Structure upon Glass during Swell Testing

The coating of poly(propylene) with a DBR structure also yielded a spectra with a stopband in the near-infrared.

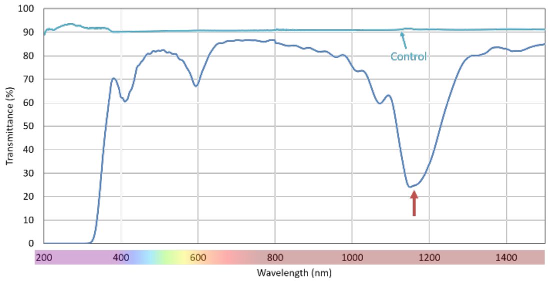

Figure 4, Spectra for DBR upon Poly(propylene) Substrate

Conclusions

A DBR structure was coated with adjustments upon a glass substrate to reflect near-infrared light at a designated wavelength. Transmittance of the near-infrared was greatly increased with exposure of the DBR coating to humidity. The re-dried coating closely matched reflectance levels of the unexposed sample. Preliminary swell testing results of the chirped structure are promising, but further research will better examine humidity exposure of the dielectric mirror structure. Considering solar irradiance at sea level upon the earth, the chirped DBR coating can reflect up to 75% of near-infrared radiation over a given wavelength range. Lastly, the DBR structure was coated successfully upon poly(propylene), showing that these coatings can be used upon other substrates to reflect the near-infrared.

References

[1] IEA. (2018). *Global Energy & CO2 Status Report*. Retrieved from https://www.iea.org/geco/electricity/.

[2] IRENA. (2018). *Global Energy Transformation: A Roadmap to 2050 (2019 Edition)*. Abu Dhabi.

[3] IEA. (2018). *Air Conditioning Use Emerges as One of the Key Drivers of Global Electricity-Demand Growth.* Retrieved from https://www.iea.org/newsroom/news/2018/may/air-conditioning-use-emerges-as-one-of-the-key-drivers-of-global-electricity-dema.html.

[4] Eljarrat, A. (2015). Quantitative Methods for Electron Energy Loss Spectroscopy. (PhD Thesis). University of Barcelona. Barcelona. Spain.
[5] Balzer, A. (2019). Metal Oxide Hydrates as Optically and Photonically Versatile Species in Inorganic-Organic Hybrid Materials. (PhD Thesis Proposal). Georgia Institute of Technology. Atlanta, GA. USA.