# Optofluidic Smart Glass with wide angular performance

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## ABSTRACT

Smart glass or switchable transparency panels are being commercialized for applications ranging from privacy panels to controlling solar load for buildings and vehicles. However, the technologies that have been developed such as electrochromic, polymer dispersed liquid crystal, and suspended particle devices are complex and expensive, and additionally switch from partial transparency to a tinted or scattering state, not having a highly reflective state, which limits applications. Our group has developed an optofluidic smart glass which should have 10x lower cost than current technologies. It is based upon a reflective structure that switches to transmissive by introducing an index-matching fluid. Previously, we have shown such a panel that consists of a solid plastic corner-cube array with a thin cavity behind it. With air in the cavity the panel is highly reflective based upon total internal reflection. We have shown inexpensive index matching fluids that when pumped into the cavity result in near-perfect transparency. However, our corner-cube array panels suffer from transmission at angles larger than 20 degrees in the reflective state. This transmission is refractive passing oblique rays at a different angle than line-of-sight, but nonetheless compromises performance. Here, we show a two-layer structure consisting of two one-dimensional solid corner reflector arrays with the layers having rotated axes. Rays beyond the TIR angle for one layer are refracted below the TIR angle for the second layer. Each layer has a cavity layer for introducing index matching fluid, and we show high transmission switching up to 60 degrees.

**Keywords:** Smart Glass, optofluidics, retroreflectors

## 1. INTRODUCTION

There is a great interest in variable or switchable transparency large-area panels for a variety of reasons.[1] Here, a distinction should be made between an intelligent Smart Glass, which will automatically vary transparency in response to temperature or other parameters, and active Smart Glass which will vary or switch transparency in response to an electrical control signal, and this paper is concerned with the latter. As such, active Smart Glass can be considered a form of optical modulator, or device which varies optical transmission vs. voltage. The most commercial forms of optical modulator are Lithium Niobate electrooptic modulators and Liquid Crystal Displays. The former varies optical transmission via an electrooptic change of refractive index, has picosecond response time, and is used to encode communication data on optical fiber. The latter varies optical transmission via a movement of liquid crystal molecules, has microsecond response time, and is used in displays. One can see that the form of optical physics used is adapted to the application.

For smart windows or other types of such large panel devices, the most common technology used is Electrochromic.[2] Electrochromic Smart Glass consists of layers of material, for which when voltage causes ions to move from one layer to another, optical transmission varies. The Electrochromic effect illustrates a further distinction of smart glass technologies: it causes a variation from transparency to absorption, rather than transparency to reflection. As such the Electrochromic effect is ideal for applications such as shading, as in varying the reflection of automobile rear-view mirrors. For applications such as adjusting solar transmission through building windows, it should be considered that Electrochromic shading will cause absorption and heating of the windows.

The next common technologies for smart windows are Suspended Particle Devices[3] and Polymer Dispersed Liquid Crystal.[4] Both of these technologies have suspended particles or liquid crystal droplets, respectively, which are

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randomly oriented in the zero-voltage state. For the former, the random orientation results in forward-scattering and absorption in the particles, so, like Electrochromic, the non-transparency state is absorptive. When voltage is applied, the particles align, lowering the scattering and raising the transparency. For the latter, the droplets result in scattering, and so illustrate a further distinction of optical effect, reflective scattering in the non-transparent state. When a voltage is applied, the droplets align and closely match the refractive index of the matrix, raising transmission. For both of these technologies, there is current in the transparent state, resulting in power consumption on the order of 5-20 $W/m^2$.

The continued aim of this paper is not to disparage any particular technology in favor of another, as clearly, each has its benefits and drawbacks. Rather, it is to explore the degree of simplicity that may result in the desired optical effect, and hence possibly lower the cost. The existing technologies are complex. While it is difficult to precisely estimate the cost of current smart glass technologies due to the lack of widespread adoption, it appears to be in the hundreds of dollars per square meter at least, perhaps thousands. Lower complexity should result in lower cost and increase adoption. In considering different effects that may result in optical modulation or switching, it should be appreciated that something must move. The simplest example is a shutter, and a reasonable example here are double-pane windows with motorized built-in blinds. Here, what is explored is a technology based upon moving a liquid fluid into a panel.[5-7] Our's is not the only exploration of variable transmission panels based upon fluidics. Ref. 8-9 show a relatively simplistic concept of introducing a colored liquid between two flat panes of glass to vary solar transmission. In our published work, one of the panes incorporates an array of corner-cube solid retroreflectors. The faceted surface is inward (figure 1). By introducing a fluid whose refractive index matches that of the pane, the reflections are greatly reduced resulting in near-transparency. Thus our optical effect has differences to the technologies listed above: first it is not a modulator, per se, with variable transmission, but rather a switch, that can go between transparent and non-transparent states. Second our non-transparent state is not scattering or absorptive, but retro-reflective. This may have advantages in certain applications, particularly varying solar load on/in buildings, for two reasons: one it is not absorptive which would result in heating of the panel, and two since the reflection is retro-reflective, it avoids a blinding effect on people in the environment, and further results in sunlight being reflected directly back into space, avoiding atmospheric absorption and resulting climate change effects. Thus besides potentially lower cost, this form of Smart Glass may have certain performance advantages. In regard to making a variable transmission device, in principle a dye could be introduced into the index-matching fluid in a variable fashion, although this has not been explored. Ours is not the only group exploring this fluidic/retro-reflective Smart Glass.[10] In [10], the retroreflective pane was fabricated with a molding procedure, and a panel with cavity formed apparently by gluing panels together, resulting in some degradation in performance based upon the photograph shown. Our devices have been made fully-integrated with a 3D printer. (In terms of ultimate manufacturing, we believe the device should be fabricated using injection molding.) In [7], we show transmission switching from 8 to 85 % measured using an integrating sphere, with photographs showing clear retroreflection and transmission states. The 3D printing material used was Veroclear, and the index matching fluid was methyl salicylate (wintergreen oil). It's cost is $36/gallon,[11], and freezing point is 16.5 F.

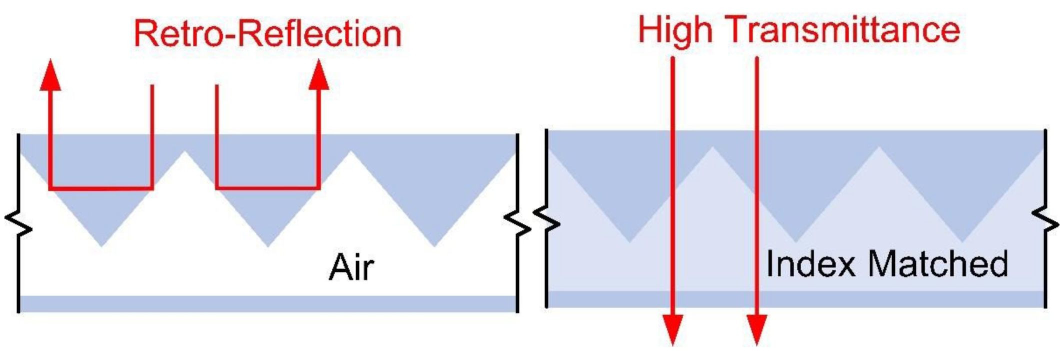


Figure 1: Drawing of our published Smart Glass panel, consisting of cavity behind solid corner-cube retroreflector array. When cavity is filled with index-matching fluid, structure switches from reflective to transparent.

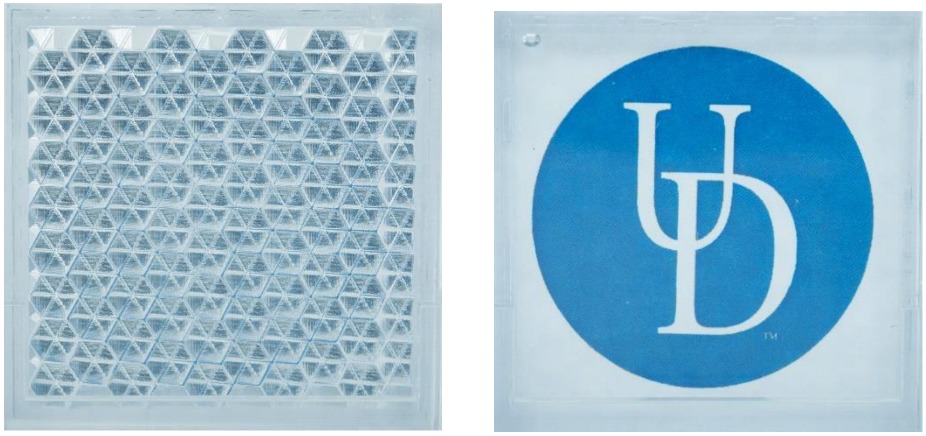

Figure 2: Photographs of corner-cube design with air in the cavity (left), reflective, and (right) with index-matching fluid, becoming transparent revealing logo behind it.

Two problems with the existing optofluidic Smart Glass were illustrated in [7]: one was that, while we showed cycling with no degradation in performance after the second cycle, from the first to the second cycle, reflection in the reflective (dry) state went from ~ 90 % to ~ 60 % due to retention of some of the fluid. We are exploring the use of coatings to avoid the fluid getting stuck which is the subject of a further publication. The second issue was the limited angle-of-incidence of the device, resulting in reflection in the reflective state going from ~ 90 % at zero degrees to ~ 40-50 % at 30 degrees. We address this second issue here, showing and measuring an improved dual-cavity design that maintains reflection in the reflective state > 75 % up to 60 degrees angle of incidence.

## 2. Angular Response of Corner Cube Array retroreflecting Smart Glass

Solid corner cube retroreflectors have been explored for many applications including retroreflective tags,[12,13] and their angular response studied.[14] To a simple extent, the angular response can be estimated using simple optics. Since the normal axis to a corner cube reflector is the (1,1,1) axis in cartesian coordinates, the angle of one of the facets is the angle between the (1,1,1) vector and the (1,1,0) vector, or cos-1(root(2/3)), or $\theta_f$=35.3 degrees. The maximum angle of incidence for retro-reflection can be at least partially understood by calculating the maximum angle for which the refracted ray undergoes Total Internal Reflection (TIR) at the first facet.

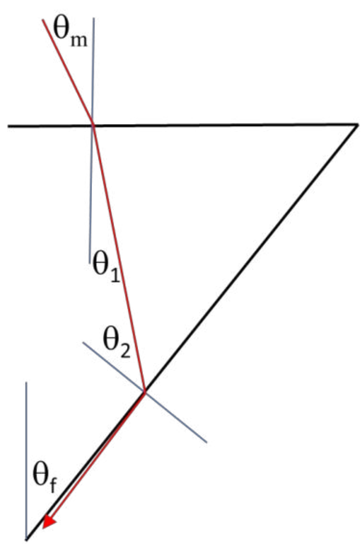


Figure 3: Ray incident on solid corner-cube retroreflector at TIR condition for first facet.

If the refracted angle at the top surface is $\theta_1$, then the angle of incidence at the first facet is:

$$\theta_2 = 90^o - \theta_f - \theta_1, \tag{1}$$

where

$$\sin(\theta_m) = n\sin(\theta_1). \tag{2}$$

The TIR condition is satisfied by:

$$\sin(\theta_2) = 1. \tag{3}$$

Solving for the corner-cube facet angle, and n=1.52 for Veroclear, the maximum angle is 20.9°. Thus, our previously published result that the structure becomes less reflective at incident angles greater than ~ 20 degrees is to be expected.

## 3. Crossed Prism design

To achieve a greater angular response, a retroreflective design was replaced with a crossed-prism design.

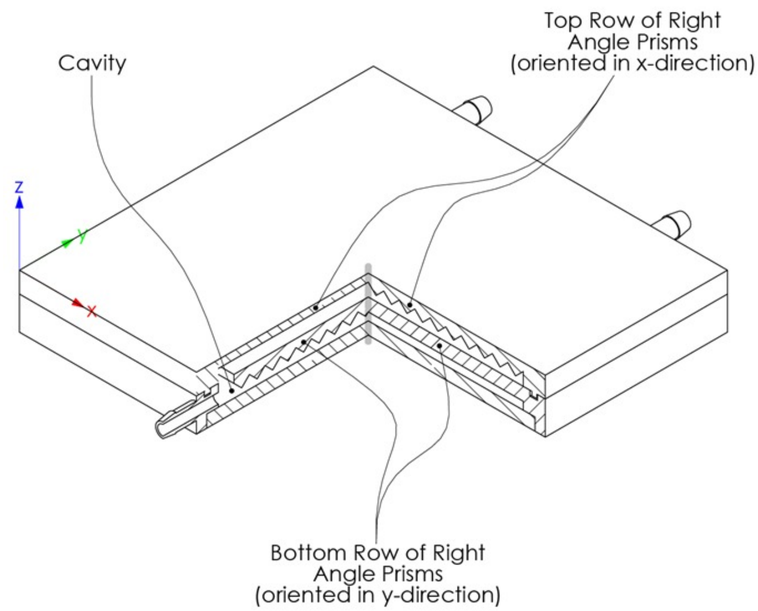


Figure 4: The wide angular response design consists of two 1-dimensional prism arrays with their axes rotated ninety degrees. There are thus 2 cavities.

This design consists of two 1-dimensional "corner-cube" layers with the "corner-cube" axes rotated ninety degrees with respect to each other. Here "corner-cube" in quotes is to guide the reader to understanding the optics. A 1-dimensional "corner-cube" is easy to understand since it can be drawn, and a ray in the plane of the paper would be retro-reflected. Any rays not in the plane would not of course. Referring back to figure 3, imagining that drawing showed the cross-section of a 1-dimensional "corner-cube," with $\theta_f$=45 degrees, a ray in the plane of the drawing would be retroreflected. At first glance, since the facet angle is larger, things appear worse with respect to angular response, since the TIR condition for the first facet is a lower angle since the facet angle is larger. However, a ray thus transmitted by the top layer will be reflected by the second layer. To understand this, it should be appreciated that for a 1-dimensional "corner-cube," rays out of the plane of the drawing of figure 3 will have a larger angle with respect to the first facet. Thus, rays out of the plane will tend to be more reflected. Thus, a ray transmitted by the top layer will be directed along the axis of the second layer, and thus will be in a TIR condition for the second layer's facet and be reflected. Rays will not generally be retroreflected, and will not generally be specular, but will be directed back in the direction they came from.

To measure the reflection of the smart glass designs, an integrating sphere thus needs to be used. A rotatable stage held the smart glass at the opening of the integrating sphere.

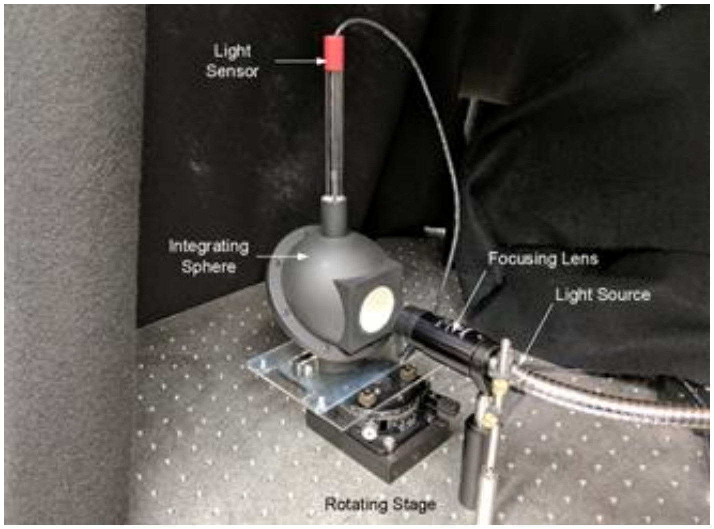


Figure 5: Experimental setup for measuring transmission of TIR smart glass designs vs. angle of incidence.

Figure 6 shows reflection of the corner-cube and crossed-prism designs as a function of angle of incidence.

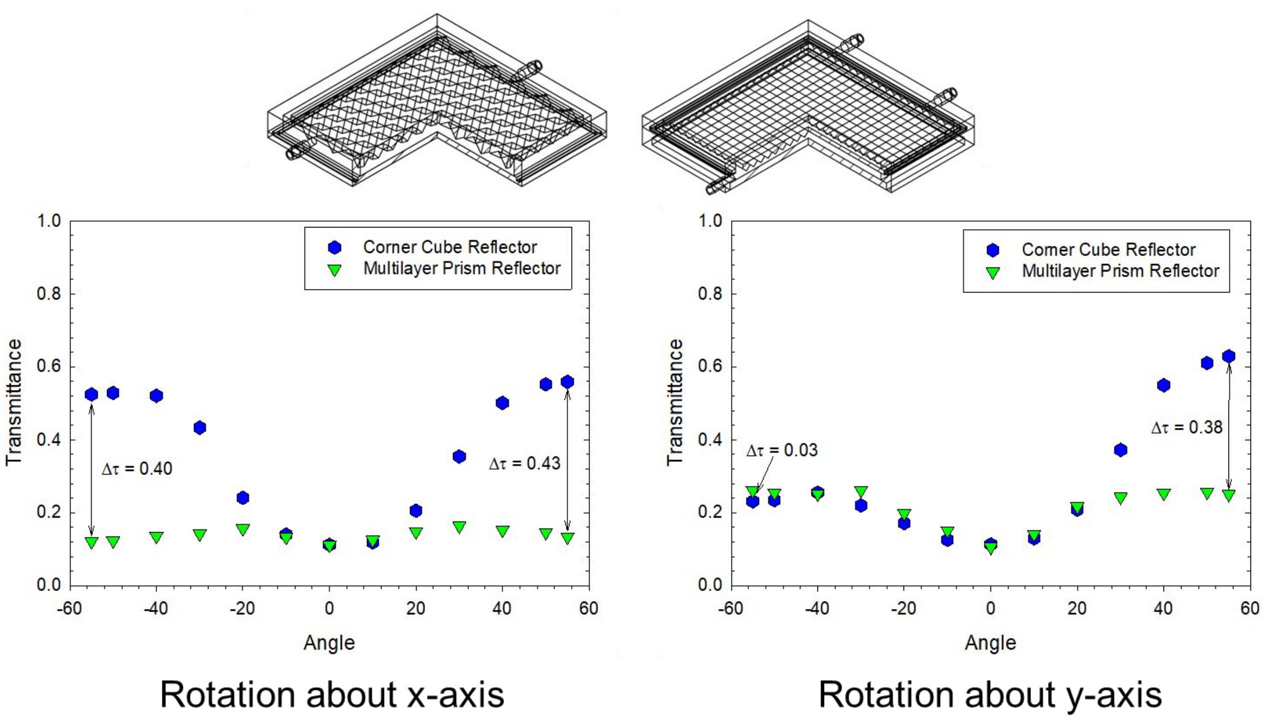


Figure 6: Measurements of the transmission vs. angle of incidence (with air in the cavities) of the published corner-cube design (blue) and crossed-prism design (blue), with angle of incidence along x and y axes.

As can be seen in Figure 6, the corner-cube design suffers higher transmission in the reflective state at angle of incidence greater than ~ 20 degrees. Note that the variation in the transmission of the corner-cube design vs. angle depends upon the axis the angle is varied along, since a corner cube does not have symmetry along perpendicular axes in the plane. The corner-cube design has transmission in the reflective (air) state up to ~ 60 % at 60 degrees angle of incidence.

Conversely, transmission of the crossed prism design in the reflective state remains below 25 % up to 60 degrees angle of incidence. In fact, theoretically there should be no transmission. Again discussing rays, ones incident normally are retroreflected. If the ray is angled along the axis of the top prism, the TIR condition will be maintained, since the angle at which the ray is incident upon the facet of the top layer will only increase. Thus, there should be no transmission of any ray at angles along the axis of the top layer. If rays are angled perpendicular to the axis of the top layer, at angles greater than ~ 6 degrees, they will be transmitted down to the second layer. However, those rays transmitted through the first layer will be angled along the axis of the second layer, and thus can only be beyond the TIR condition for the facet of the second layer. Thus, theoretically, transmission of the crossed prism design should be zero in figure 6. The reason it is not is due to surface roughness of the facets that results in some scattering and forward transmission. The reason the transmission is different for angles of incidence along different axes is different, is due to the effect of surface roughness being different depending upon which layer (which prism axis) is the top layer.

Note that transmission in both designs remains above 80 % in the transparent (fluid) state at angles of incidence up to 60 degrees over the visible spectrum. There is no theoretical dependence of transmission in the transparent state on angle or design since the facet reflection is theoretically zero. The reason transmission is not 100 % is due to material absorption and scattering.

## 4. Conclusion

We have extended our optofluidic smart glass work reported in [7], which showed a TIR panel consisting of a solid corner-cube retroreflector array backed by a cavity, which when filled with index-matching fluid eliminated facet reflection resulting in transparency of the panel. That design suffers from transmission in the reflective state at angles of incidence above ~ 20 degrees, as any solid corner-cube retroreflector array would, with measured transmission as high as 60 % at 60 degrees. We have demonstrated a second design consisting of two "1-dimensional corner-cube" arrays, or prism-array layers, with two layers having their axes ninety degrees rotated with respect to each other, that theoretically would have zero transmission in the reflective state up to 60 degrees angle of incidence. We have measured this design, and found transmission remains below 25 % up to 60 degrees angle of incidence. The experimental transmission is due to surface roughness. Thus, we have shown a switched-transparency panel using fluidics with a wide angular response.

## REFERENCES

[1] Ruben Baetens, Bjørn Petter Jelle, Arild Gustavsend, "Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review," Solar Energy Materials and Solar Cells, Volume 94, Issue 2, February 2010, Pages 87-105.

[2] K. J. Patel, G. G. Bhatt, J. R. Ray, Priya Suryavanshi, C. J. Panchal, "All-inorganic solid-state electrochromic devices: a review," Journal of Solid State Electrochemistry, February 2017, Volume 21, Issue 2, pp 337–347.

[3] David Barrios, Ricardo Vergaz, Jose M.Sanchez-Pena, Claes G. Granqvist, Gunnar A. Niklasson, "Toward a quantitative model for suspended particle devices: Optical scattering and absorption coefficients," Solar Energy Materials and Solar Cells, Volume 111, April 2013, Pages 115-122.

[4] K K Raina and Pankaj Kumar, "Polymer dispersed liquid crystal composite films-droplet orientation and optical responses," Journal of the Indian Institute of Science VOL 89:2 Apr–Jun 2009, pp. 243-253.

[5] Keith Goossen, "Reflective Roof," U.S. Patent 8,635,817, Nov. 2, 2010.

[6] Daniel M. Wolfe and Keith Goossen, “Active Modulated Reflectance Roofing System to Tailor Building Solar Loads for Increased HVAC Efficiency,” ASME Proceedings | Solar Buildings, Including Solar Climate Control/Heating/Cooling, Paper No. ES2014-6386, pp. V002T10A006 (2014).

[7] Daniel Wolfe and K.W. Goossen, “Evaluation of 3D printed optofluidic smart glass prototypes,” Optics Express Vol. 26, Issue 2, pp. A85-A98 (2018).

[8] Marco Cecchi, Berardo Naticchia, and Alessandro Carbonari, “Development of a first prototype of a liquid-shaded dynamic glazed façade for buildings,” Procedia Engineering 85, pp. 94-103 (2014).

[9] Ritter, Volker; Matschi, Christoph; Schwarz, Dietrich, “Assessment of five control strategies of an adjustable glazing at three different climate zones,” Journal of Facade Design and Engineering, vol. 3, no. 2, pp. 129-141, 2015.

[10] Sangki Park and Sun-Kyu Lee, “Micro-optical pattern-based selective transmission mechanism,” Vol. 55, No. 9 / March 20 2016 / Applied Optics 2457-2462.

[11] https://www.bulkapothecary.com/product/essential-oils/pure-therapeutic-grade/wintergreen-essential-oil/

[12] Steven P. Griggs, Martin B. Mark, Barry J. Feldman, "Dynamic optical tags", Proc. SPIE 5441, Battlespace Digitization and Network-Centric Systems IV, (19 July 2004).

[13] Changping Luo, KW Goossen, “Optical microelectromechanical system array for free-space retrocommunication,” IEEE Photonics Technology Letters ( Volume: 16, Issue: 9, Sept. 2004 ) Page(s): 2045 – 2047.

[14] George H. Seward, Pamela S. Cort, "Measurement and characterization of angular reflectance for cube-corners and microspheres," Optical Engineering 38(1), (1 January 1999).