Multifunctional Smart Window based on Dielectric Elastomer Actuator

Presented by Milan Shrestha [1,*]

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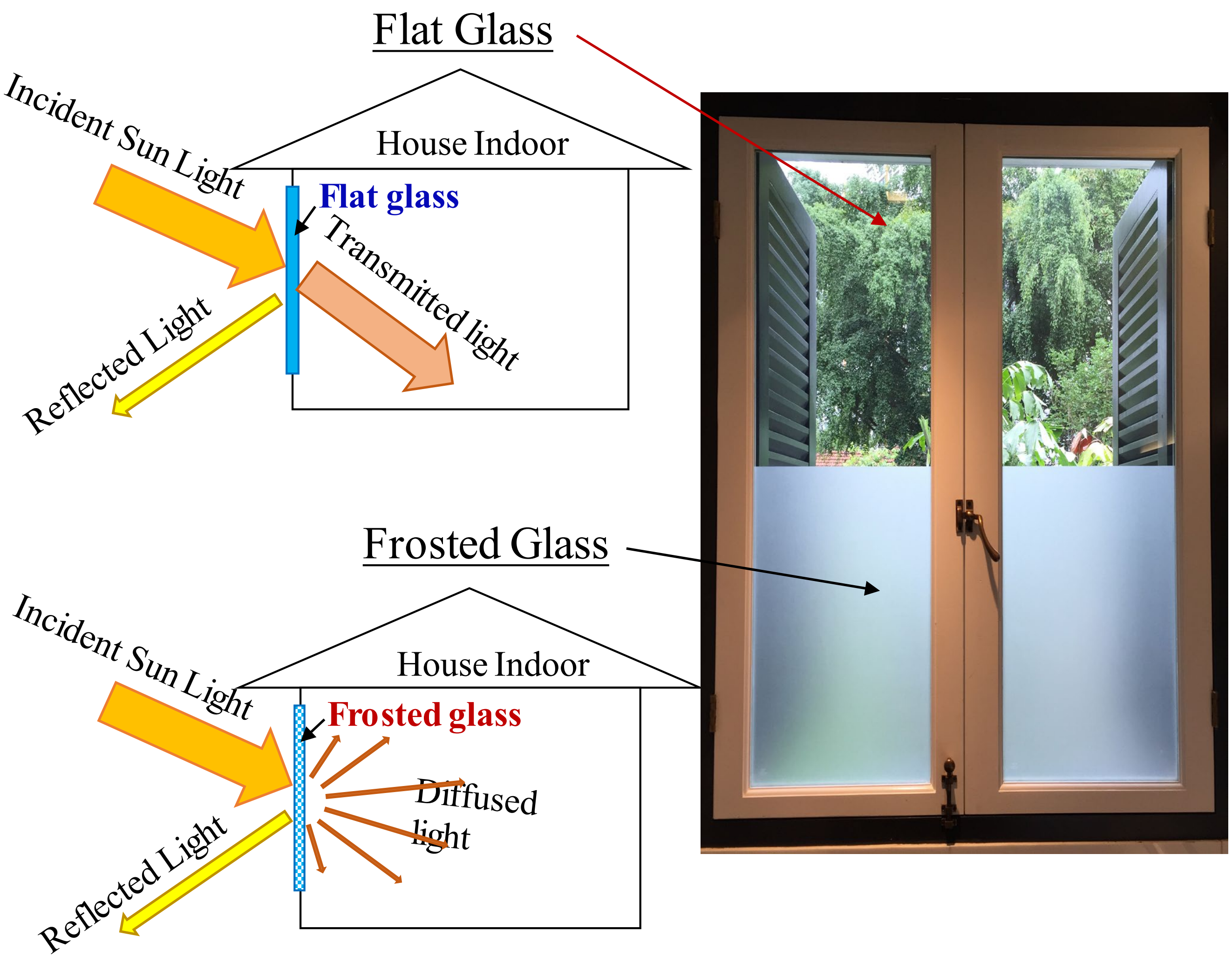
Presentation Outline

1. Introduction
   - Window glasses requirements, transparency tunable glass, transparent acoustic absorbers
2. Literature Review
3. Problem Statement\ Solution
4. Methods and Results
   - ➢Part 1: Transparency Tuning Device
   - ➢Part 2: Tunable Acoustic Absorber
5. Conclusions and Future Work

Background

- Glasses are used in high rise buildings to:
  1. **Promote daylighting**
  2. **Isolate from outdoor noise**
  3. Architectural aesthetics

Types for Glass: Optical Aspects



- **Allows direct daylight**
- **Clear visibility**
- Privacy Issues
- Direct sunlight Glare

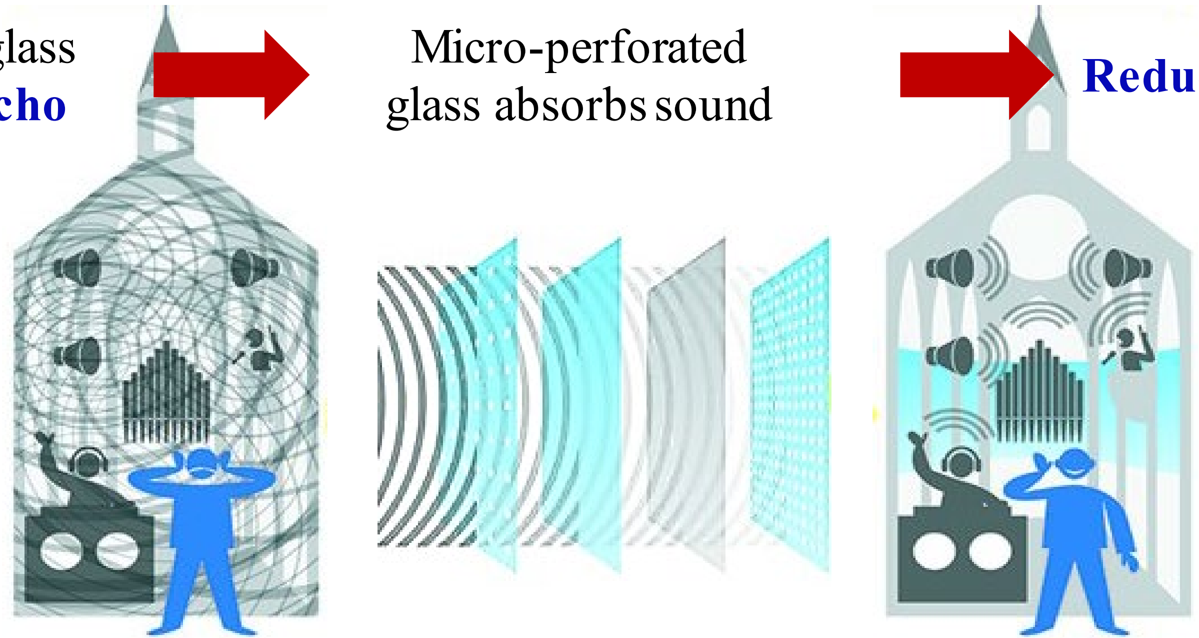
- **Diffuse light**
- **Obscure visibility**

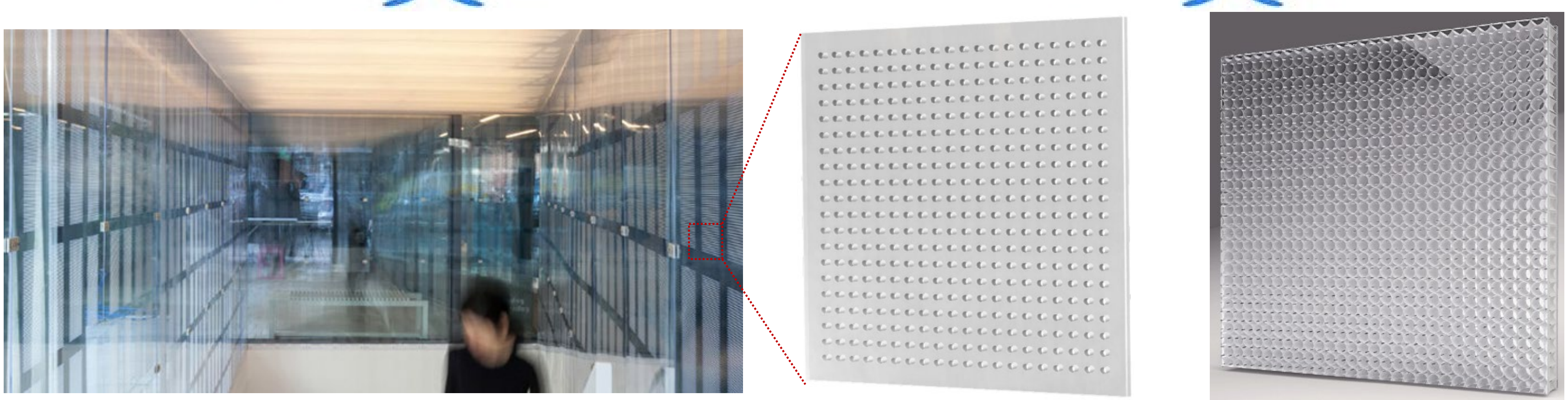
Glasses for Sound Absorption

Normal glass causes **echo**

Micro-perforated glass absorbs sound

Reduces echo





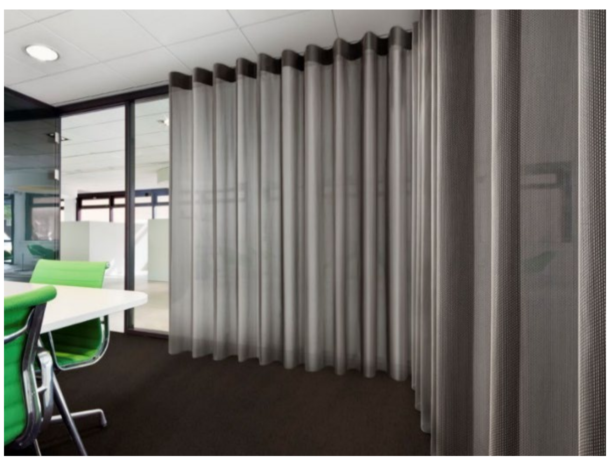
Various designs of commercial micro-perforated glass exist

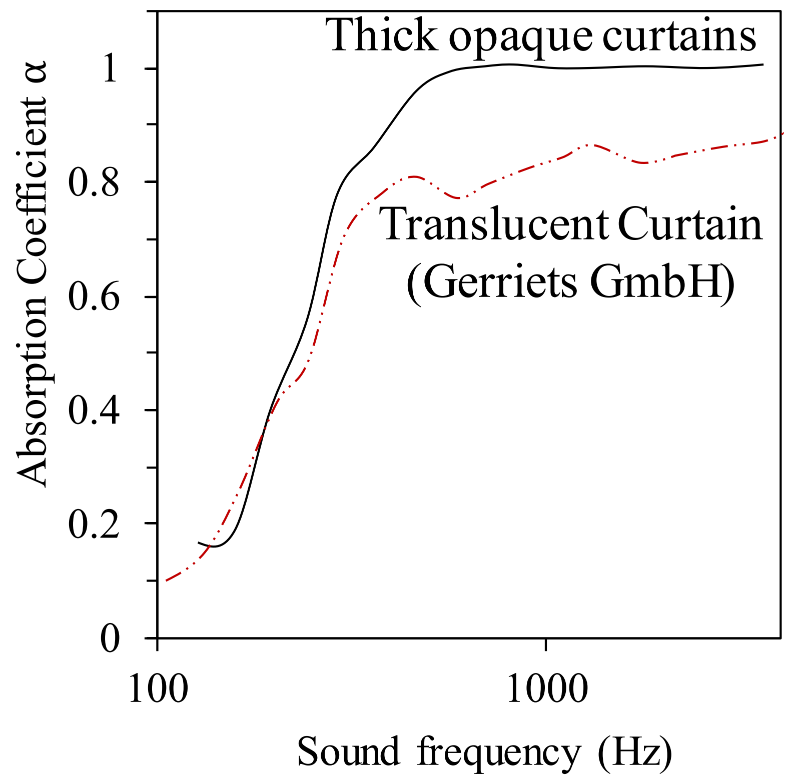
Curtains for Sound Absorption & Daylighting

- Curtains block light and absorb sound
- Adjusting is a hassle
- Recently few are designed to be translucent

Sound absorbing thick curtains

Translucent sound absorbing curtain



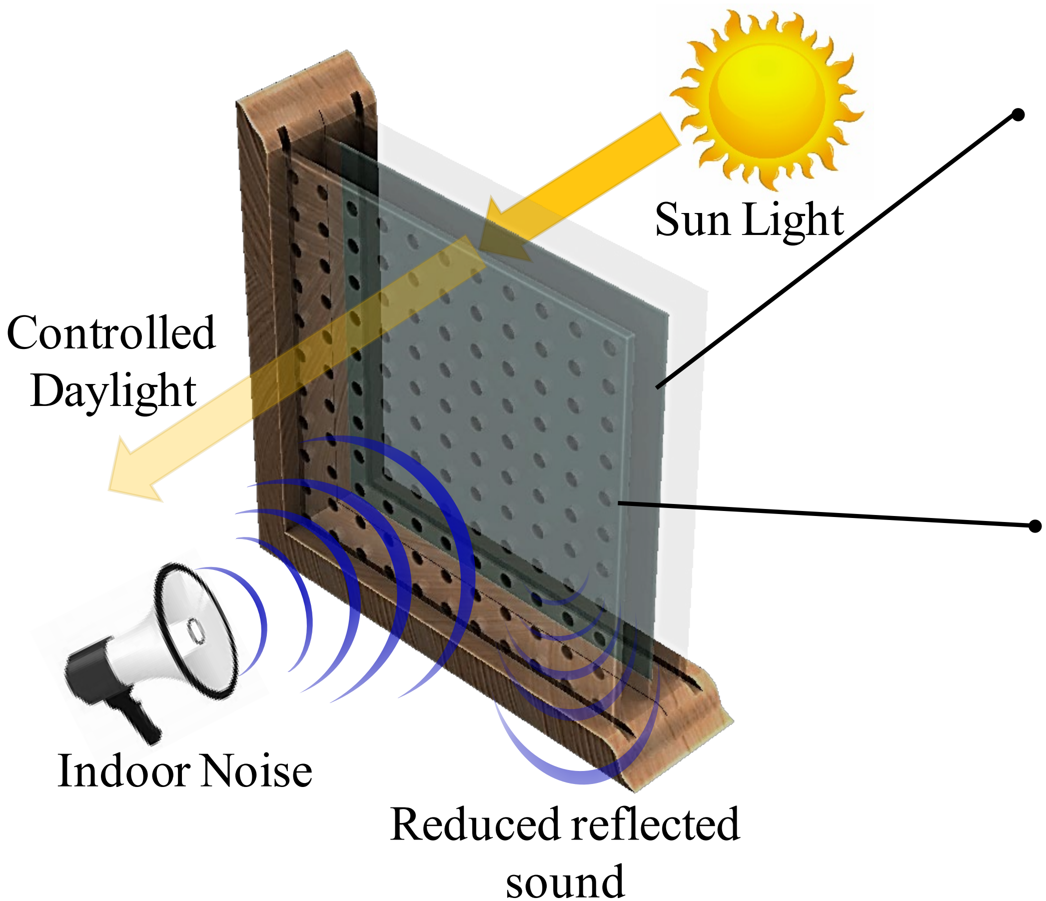


https://www.gerriets.com/media/wysiwyg/downloads/certificate/acoustics-certificate/DE-versions/gc-DE-ABSORBER-LIGHT-Schallgutachten-DIN-EN-ISO-354.pdf

Current Need: Multifunctional Smart Window

- Need a Smart Window which can
  - Control transparency and
  - Absorb sound simultaneously

- Few window devices which can perform one of the functions are commercially available



Transparency Tuning Unit

Existing Solution

1. Electrochromic glass
2. Polymer dispersed liquid crystal device (PDLC)

Noise Absorbing Unit

Existing Solution

1. Panel type absorber
2. Micro-perforated panel absorber (MPP)

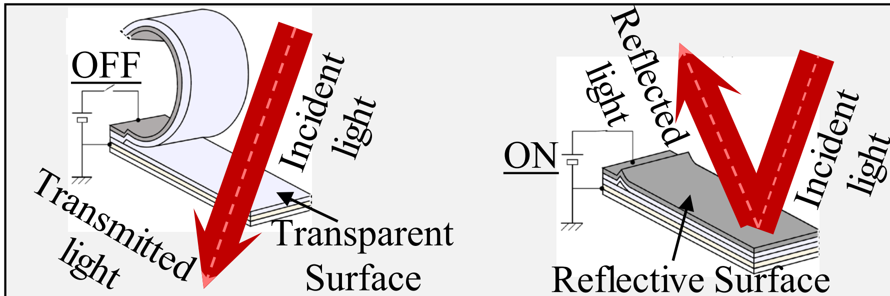
Review: Transparency Tunable Glasses

Smart Window for Transparency Tuning | **Examples**

Tuning Absorption

- Electrochromic glasses
- Suspended Particle Devices

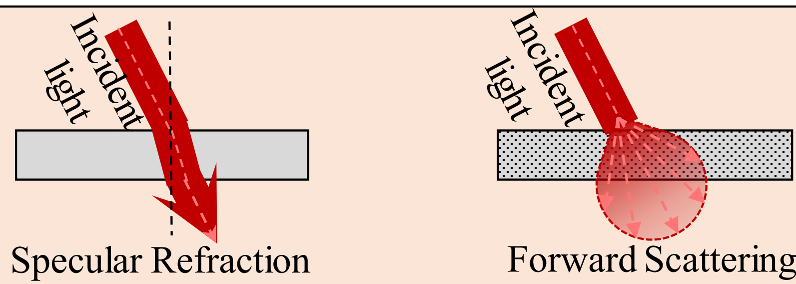
Tuning Reflection



- Micro-blinds array
- Optofludic smart glass

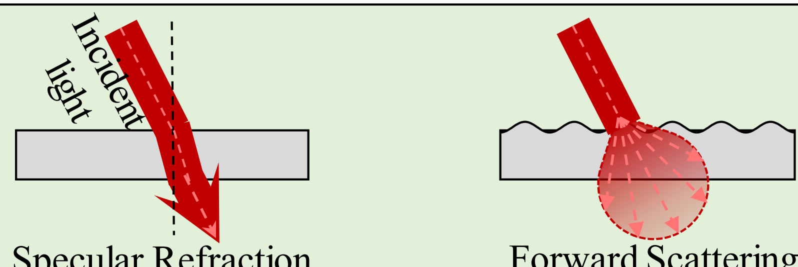
Tuning Transmission

Refractive index-change



- Polymer dispered liquid crystals (PDLC)
- Polymer filled with phase changing particle

Optical phase-change

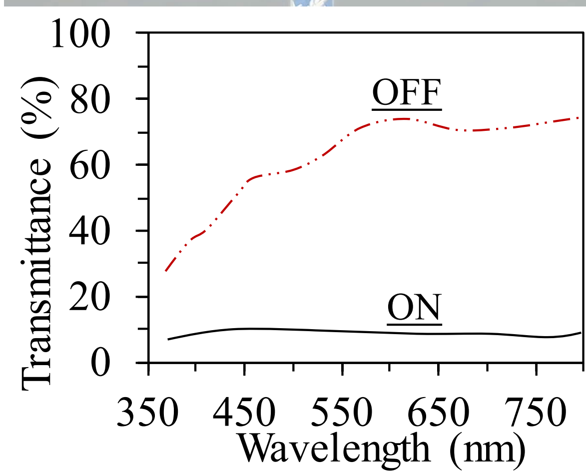


- Indentation of elastomer substrate
- Thin-film Wrinkling

Existing Smart Windows

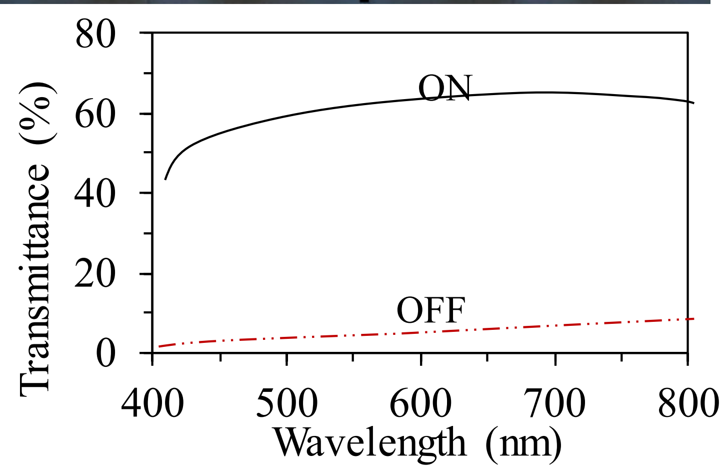
Electrochromic Glass

- Electrochemically changes color
- Tunes transmittance from **5% to 65%**
- Cost **$1000/sq.m** (viewglass)



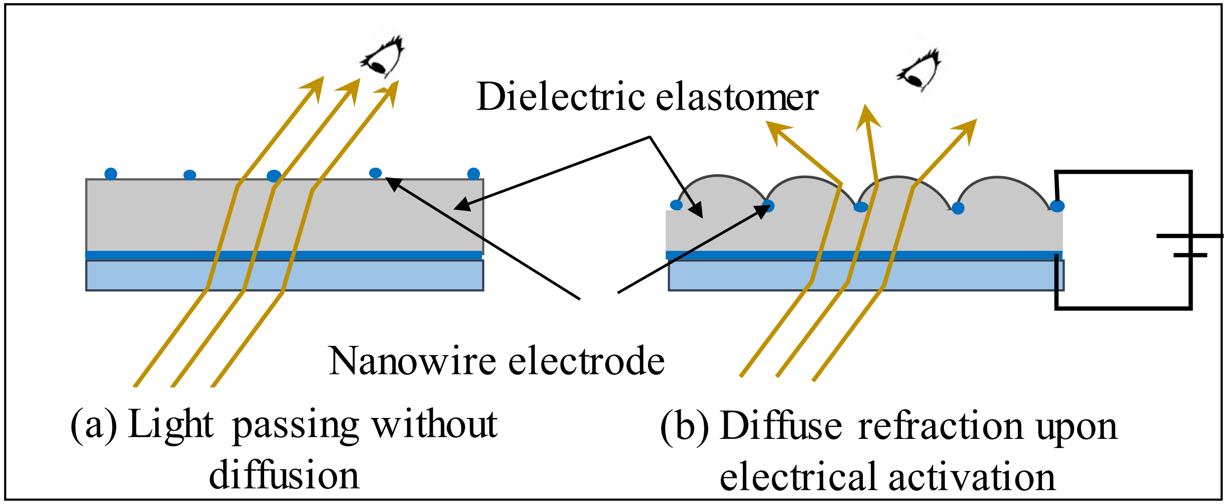
Polymer Dispersed Liquid Crystal Device (PDLC)

- Scatters light to appear opaque
- Tunes transmittance from **6% to 62%**
- Cost **($200-300/sq.m)**
- Age upon prolonged UV exposure

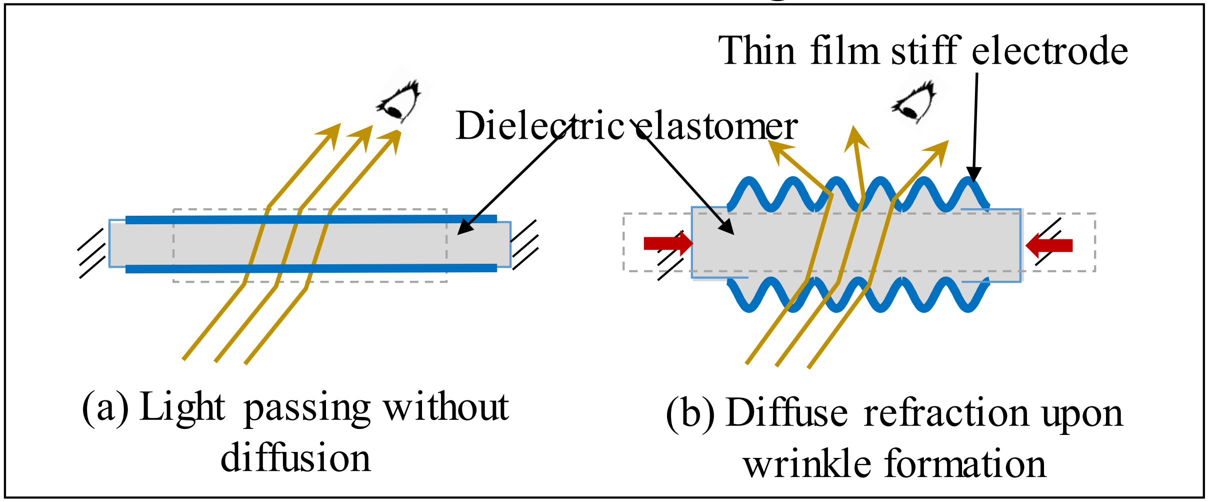


Low-cost Approach: Surface Roughening

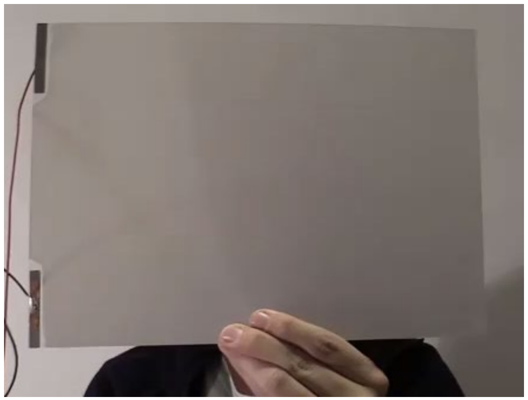
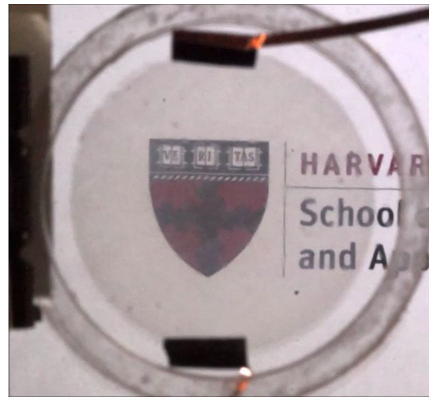
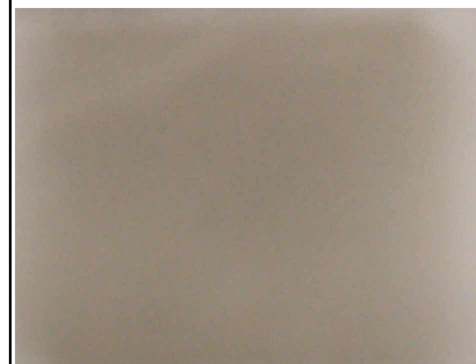
Indentation of Elastomer

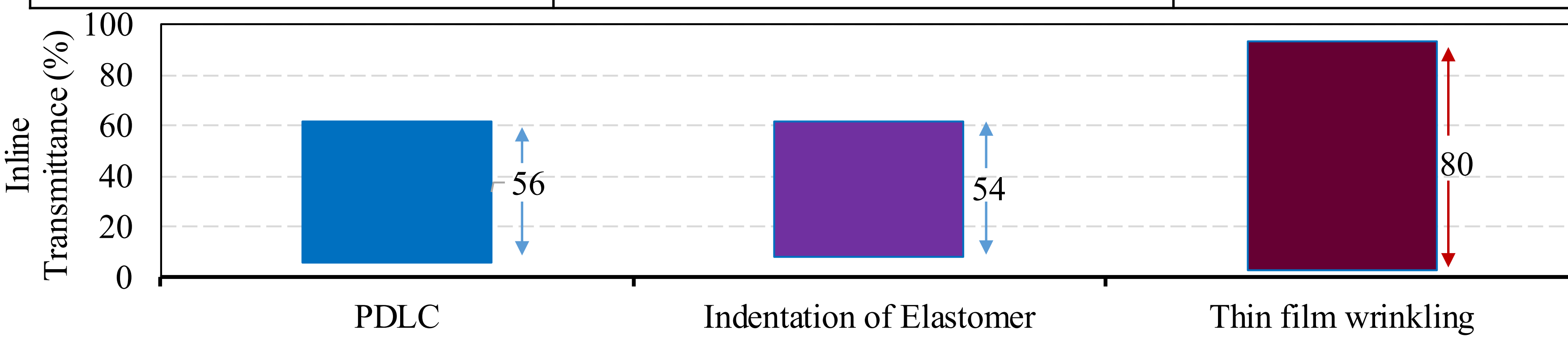


Surface wrinkling



Comparison: Existing Devices

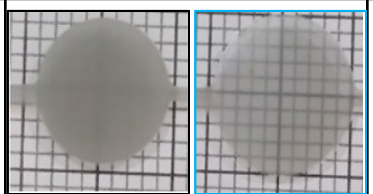
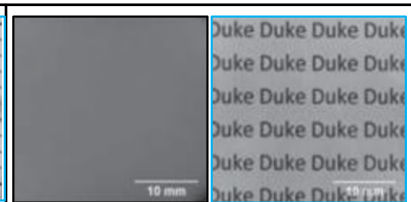
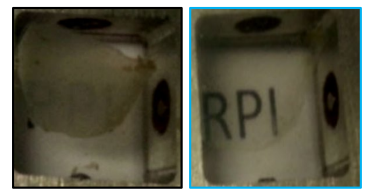
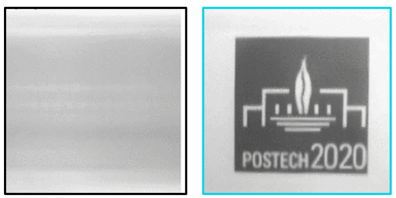
Tunable Privacy Glass		
Polymer dispersed Liquid Crystal	Indentation of elastomer substrate	**Thin-film Wrinkling**
		



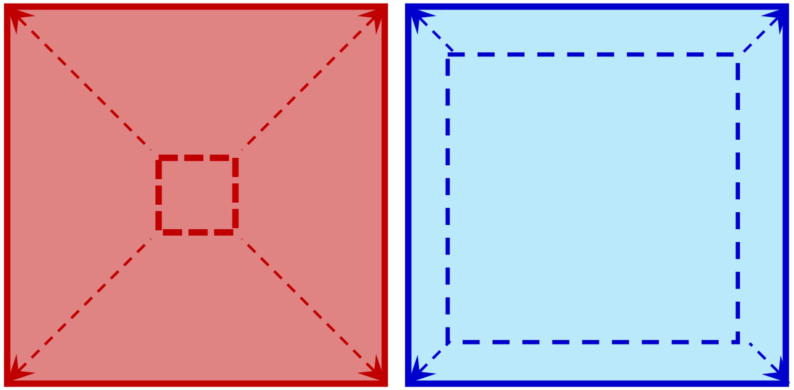
- ➢ Nanowires in indentation device scatters light and limits transmittance
- ➢ Thin-film wrinkling has larger visibility tuning range

Comparison: Thin Films Wrinkling Based Device

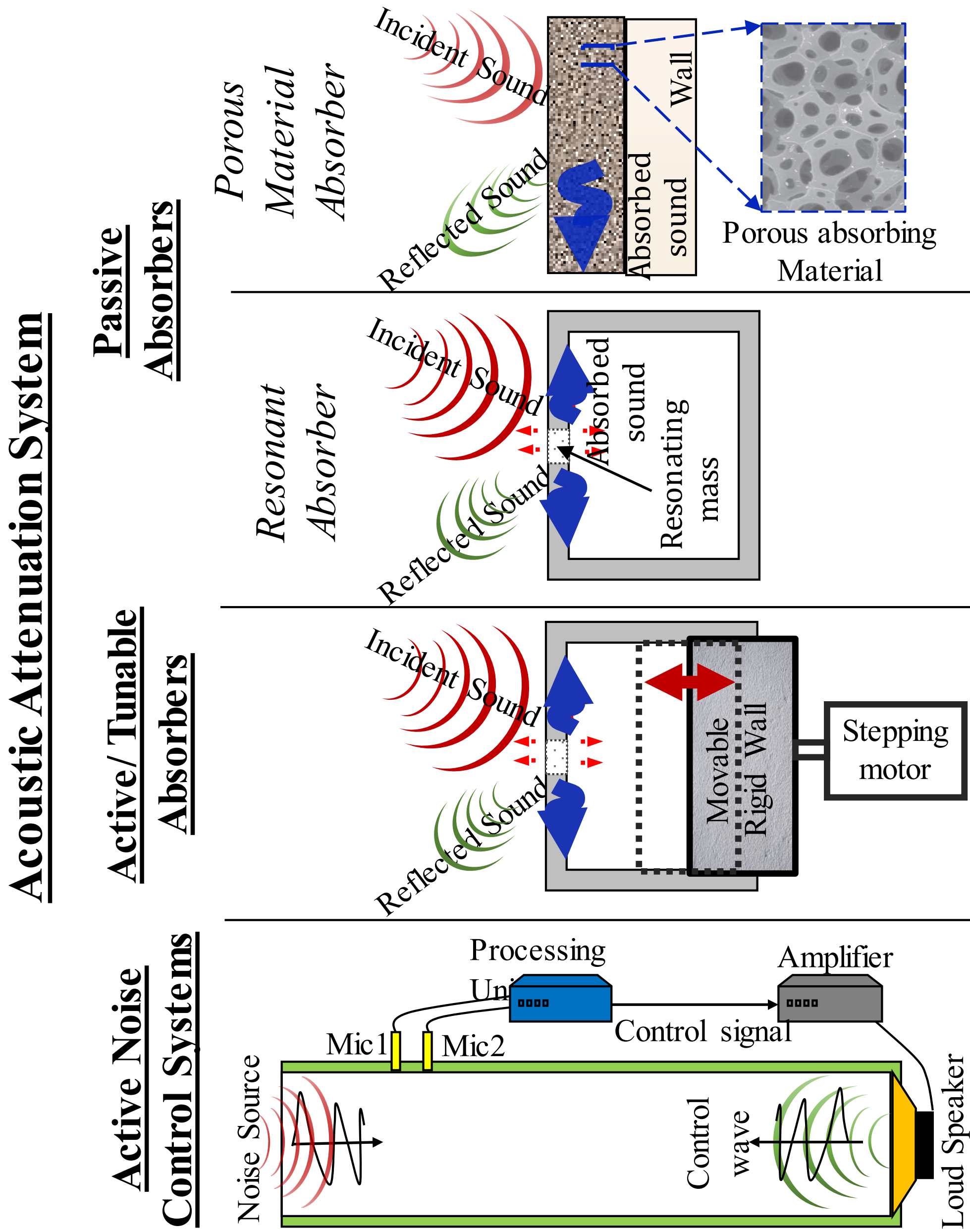
- High transparency at unwrinkled state is required
- Large in-plane compression is not applicable for window appliance

Performance Comparison of Thin Films				
Thin films	**Indium Tin Oxide**	**Gold**	**Graphene Oxide**	**Silicate (treated)**
Electrical Property	**Conductor**		**Insulator**	
Tuning visibility				
In-plane strain	37%	70%	400%	30%

- Large in-plane compression makes these devices inapplicable as window appliance



Review: Acoustic Absorbers



- Opaque

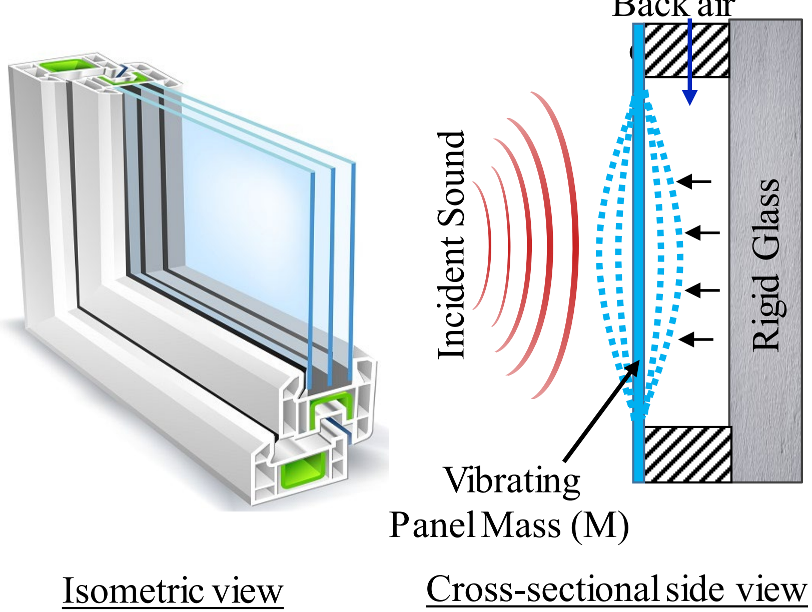
- Panel Absorber
- Helmholtz Absorber
- Micro-perforated Panel Absorber

- Variable Back-cavity
- Variable Membrane Tension (panel absorber)
- Unpractical to implement

- Small enclosed space
- Power hungry

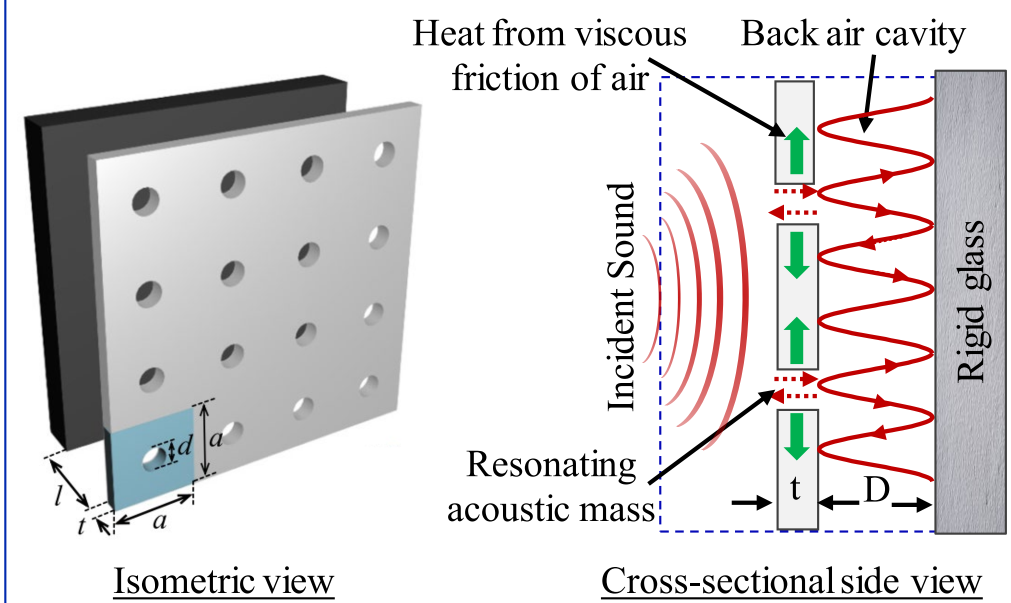
Existing Transparent Acoustic Absorbers

1. Panel absorber



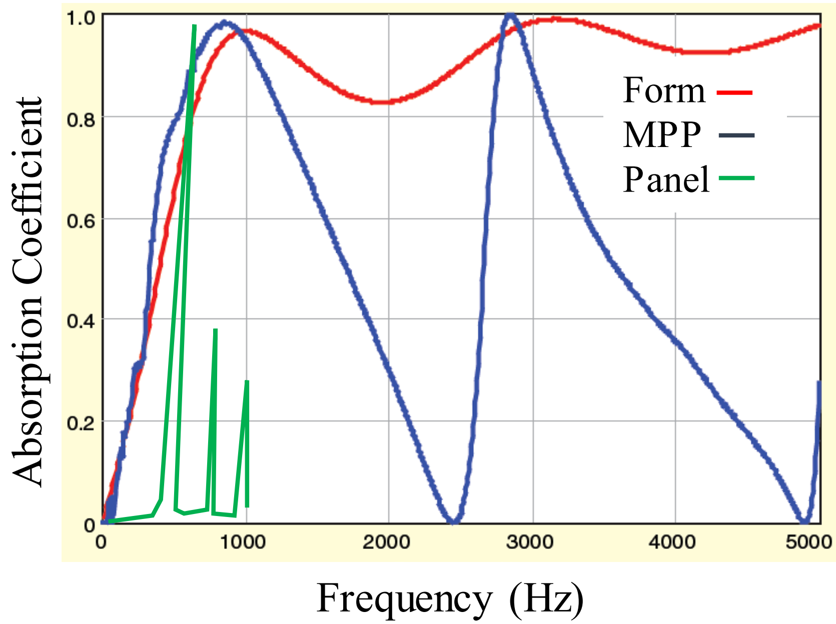
- Resonating membrane or panel absorbs sound
- Designed for fixed low frequency sound of narrow bandwidth

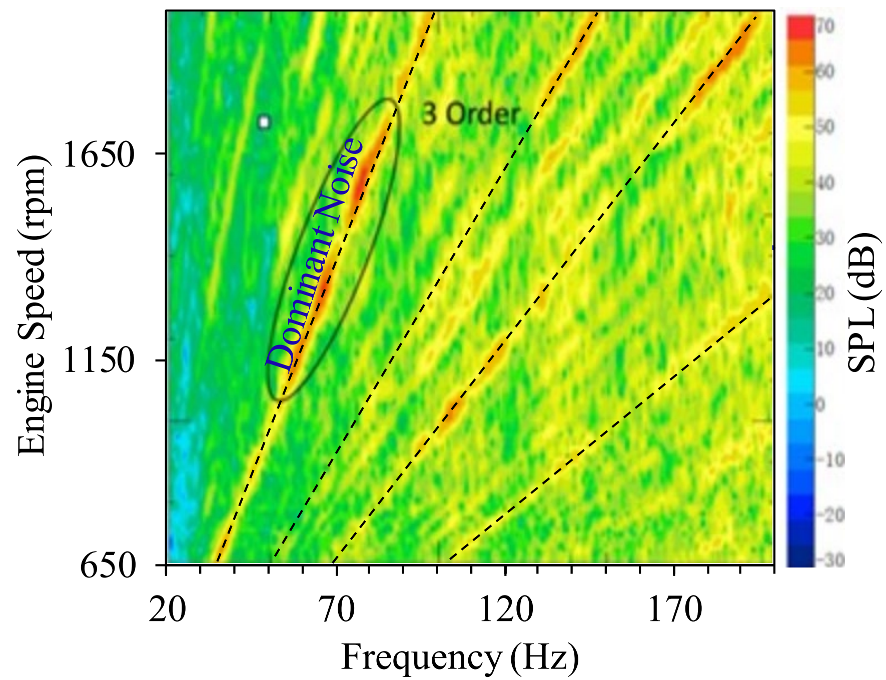
2. Micro-perforated panel absorber (MPP)

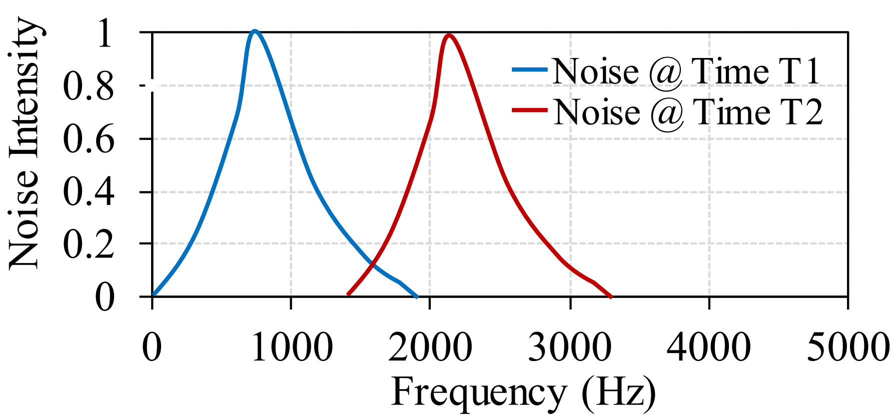


- Helmholtz resonator principle
- Resonance of air-plug in the perforations also absorbs sound
- Designed for fixed low frequency sound
- Designed frequency depends on perforation size and Membrane thickness

Comparison: Existing Acoustic Absorber







- Noise frequency changes (e.g. Engine Noise)
- MPP designed for a fixed frequency is not efficient to absorb noise of frequencies

[1] D. Herrin and J. Liu, "Properties and Applications of Microperforated Panels," Sound and Vibrations, 2011.

Motivation and Objectives

Problem Statement: Transparency Tuning

- Existing commercial technologies for transparency tuning are expensive
- Most of them have moderate transparency tuning range (e.g. 65% to 5% electrochromics)
- High continuous power consumption (e.g. 5-20 W/sq.m PDLC)
- Low cost approach using large area strain to form micro-wrinkles (e.g. >400% area change Graphene oxide)
- Low coverage to the windows due to large area strain

Problem Statement: Acoustic Absorption

- Porous absorbers are opaque
- Existing transparent acoustic absorbers have fixed narrow absorption bandwidth (e.g. panel absorber)
- They are inefficient to absorb noise with varying dominant frequency

Objectives:

1. To develop a low-cost smart window based on surface wrinkling
   - With large transparency tuning range and
   - Requires small area strain
2. To develop tunable acoustic absorbers which can adapt to broader bandwidth noise of varying dominant frequency

Method & Results

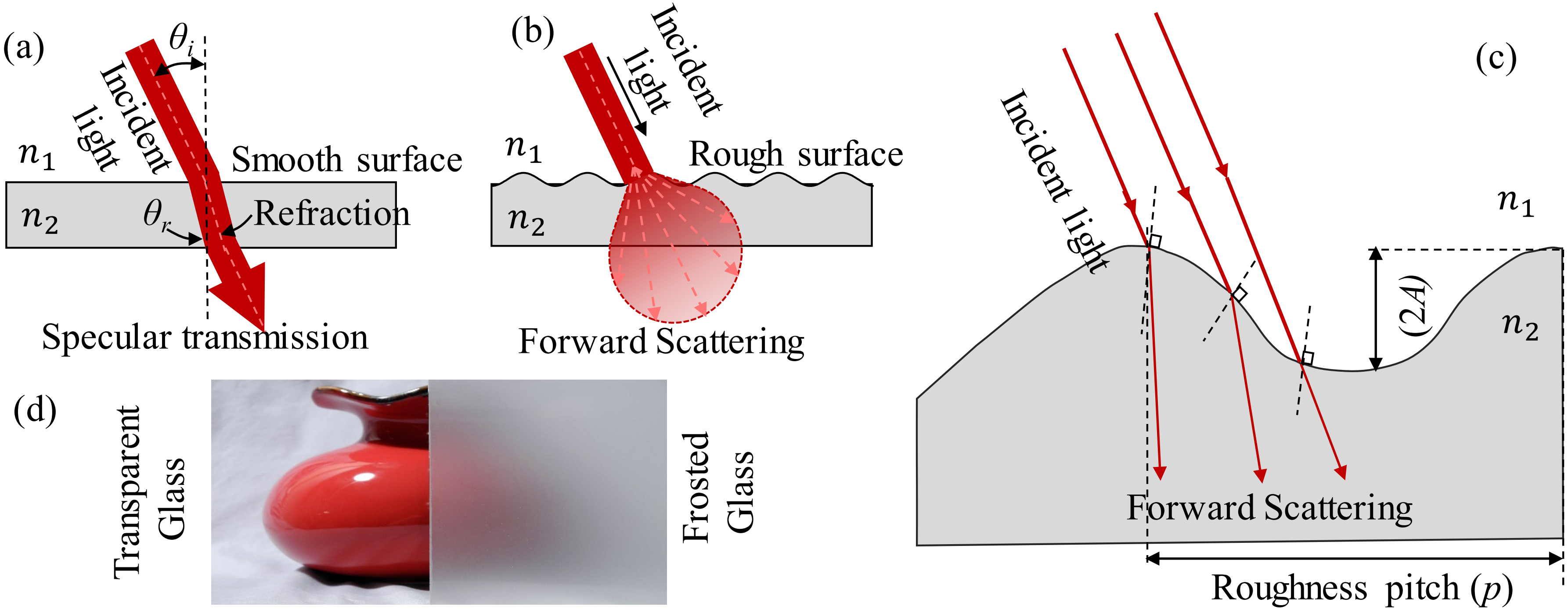
Part I

Smart Window for tunable transparency

Based on Surface-Wrinkling

Scattering of Light by Rough Surface

- Optical scattering is strongly dependent on surface roughness (σ) and refractive index mismatch



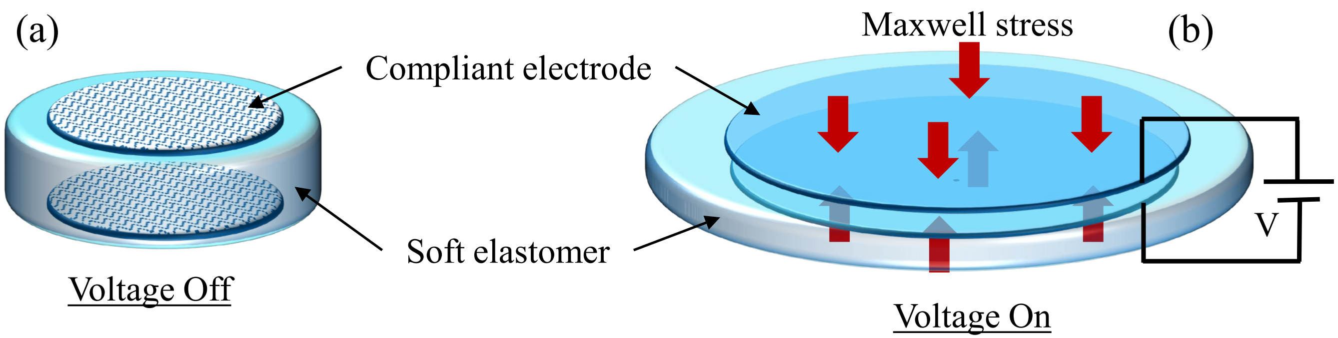
$$\text{Inline transmittance } (T_{spec}) = T.exp\left\{-\left[\frac{2\pi\sigma}{\lambda} cos\ \theta_i\ (n_1 - n_2)\right]^2\right\}$$

where, $T = 1 - R = \frac{4n_1 n_2}{(n_2 + n_1)^2}$ is the total transmittance of the medium given by Fresnel equation, n_1 and n_2 are the refractive indices of two optical media which defines the interface,
θ_i is angle of incidence, σ is the surface roughness and λ is the wavelength of light

*P. Beckmann and A. Spizzichino, "The scattering of electromagnetic waves from rough surfaces," *Norwood, MA, Artech House, Inc., 1987, 511 p.*, 1987.
**A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces. By P. Beckmann... and André Spizzichino*: Pergamon Press, 1963.

Electrically Unfolding Microwrinkles

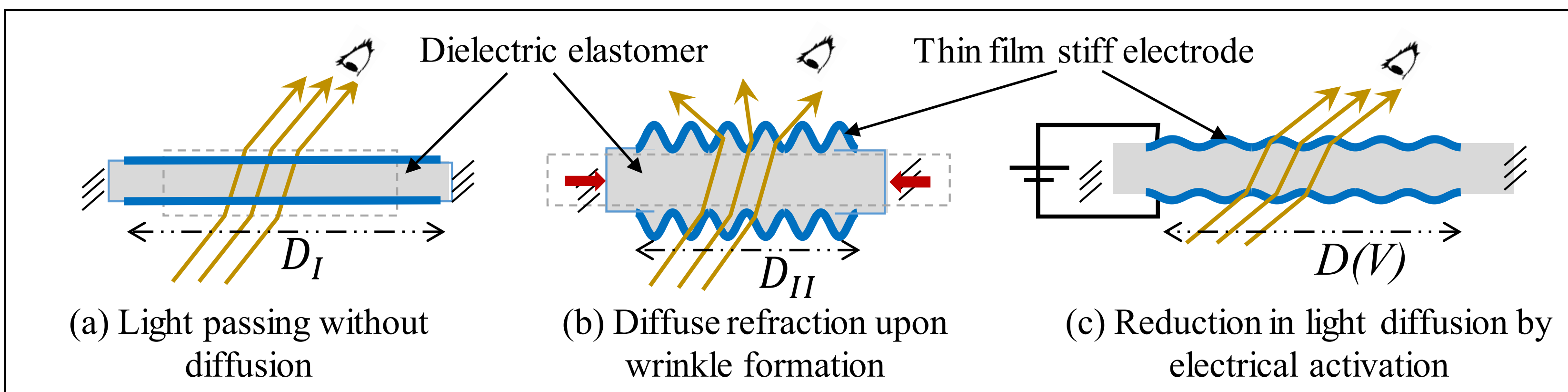
- Electrically controlling wrinkle amplitude using Dielectric Elastomer Actuators



Voltage induced strain, $e(V) = \frac{D(V)}{D_I} - 1 = e_0 + \frac{\Delta D(V)}{D_{II}}\left(\frac{D_{II}}{D_I}\right) = e_0 + \frac{\Delta D(V)}{D_{II}}(1 + e_0)$

$$\approx e_0 + (1 + e_0)\frac{\varepsilon_r \varepsilon_0}{4E_s}\left(\frac{V}{t_{II}}\right)^2.$$

where, pre-compression strain $e_0 = \frac{D_{II}}{D_I} - 1.$



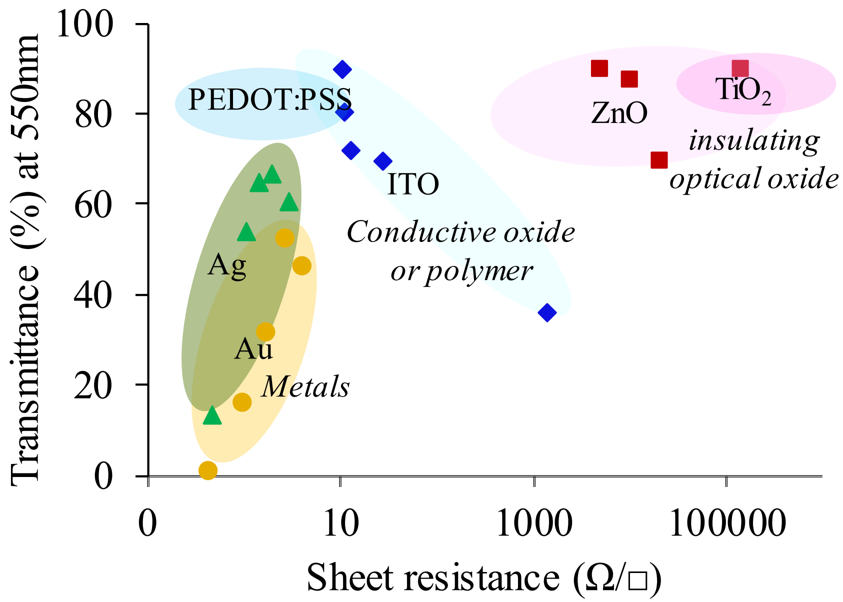
(a) Light passing without diffusion

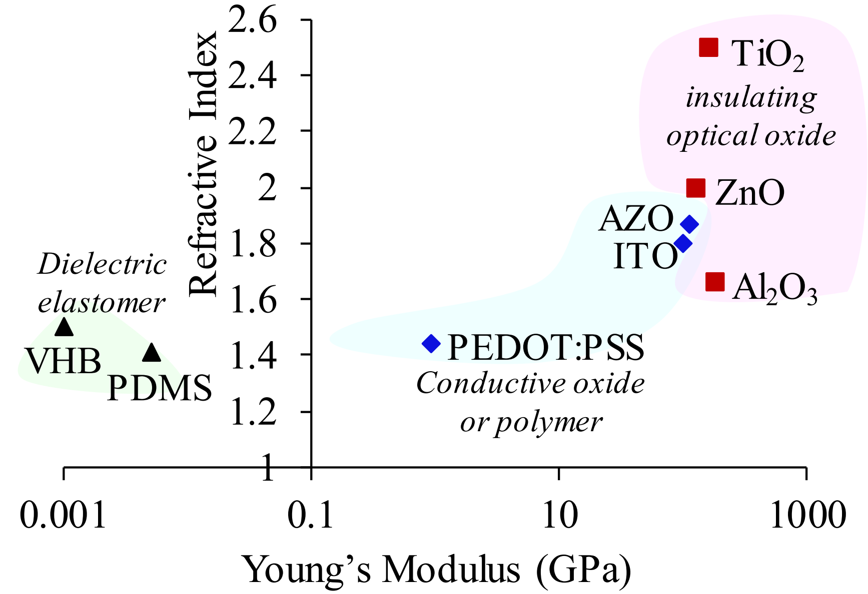
(b) Diffuse refraction upon wrinkle formation

(c) Reduction in light diffusion by electrical activation

Solution : Thin Film Material Selection

- ❑ **Problem Summary: Need for effective optical diffusion by surface microwrinkling under a small axial compression**
- ❑ Material selection criteria to solve the problems
  - ➢ Highly transparent
  - ➢ Electrically conductive
  - ➢ Stiff (So that even nanometric coating can induce large microwrinkles at small strain)
  - ➢ High Refractive index (larger refractive index mismatch is better for scattering)
- • ITO and AZO are possible but forms thermally induced wrinkles
- ❑ **Solution: Multilayer thin films of materials like ZnO or TiO_2 films and conductive materials like PEDOT:PSS (poly (3, 4-ethylene dioxythiophene)-poly styrene sulfonate)**



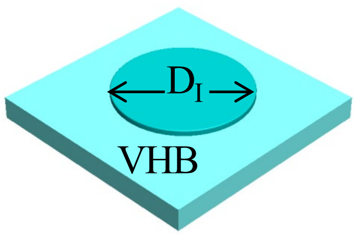


Experimental Work: PEDOT:PSS/TiO_2 Coating

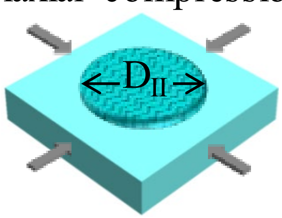
- Titanium dioxide (TiO_2) thin films deposited at room temperature (38.79nm thick using E-beam evaporation deposition, Coaxial Power Systems) on 3 times pre-stretched VHB4905 membranes
- PEDOT:PSS is spin-coated (38.79nm thick) or inkjet printed on TiO_2 thin films

Fabrication procedures

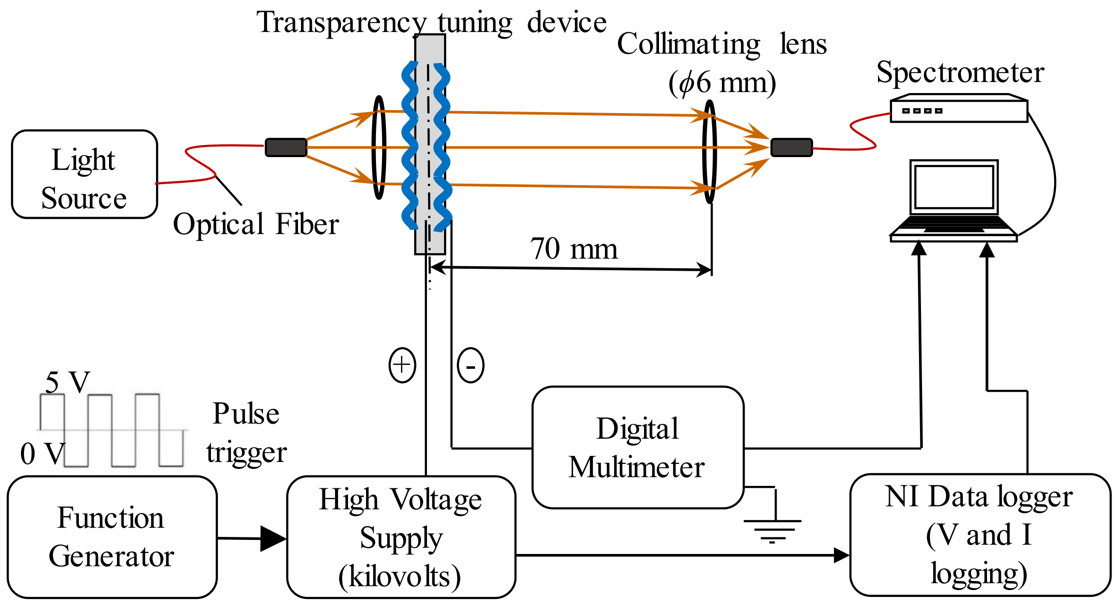
i) Thin film deposition



ii) Biaxial compression



Measurement Setup

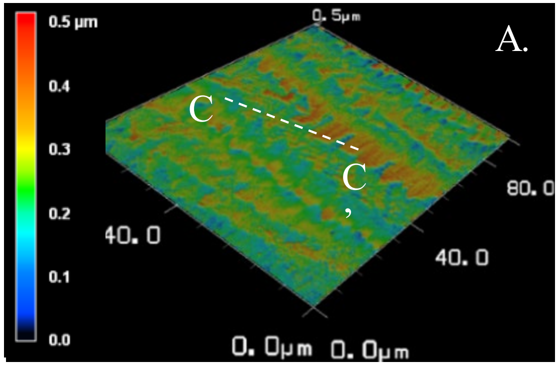


- Inline transmittance measurement: Spectrometer (AvaSpec-USB2 Fiber Optic), Halogen light source (AvaLight-Hal-S-Mini)
- Electrically activated : by high voltage power supply; current and voltage are logged; cyclic activation controlled by function generator

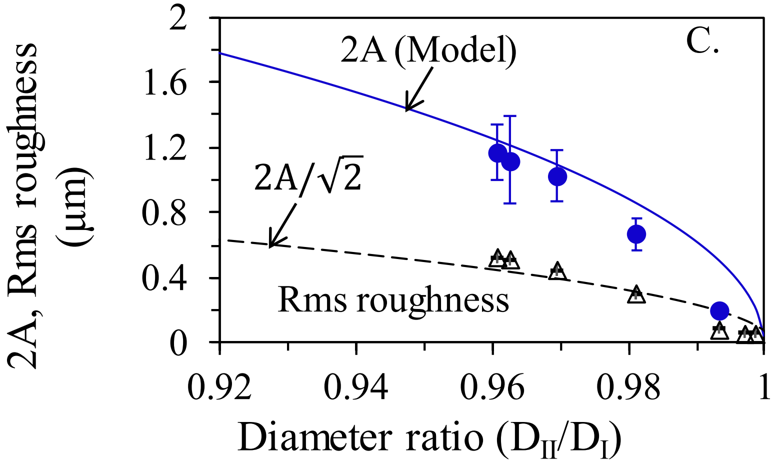
Results: Wrinkling of TiO_2/PEDOT:PSS Thin Films

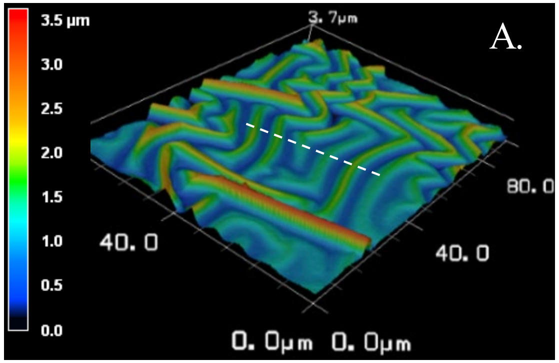
- Wrinkles with amplitude of 0.585±0.085μm and pitch of 7-8μm forms under 4.5-5% radial compression
- Wrinkles formed at 5% compression strain, fully unfolds upon 2.85kV activation of DEA

3D Profile

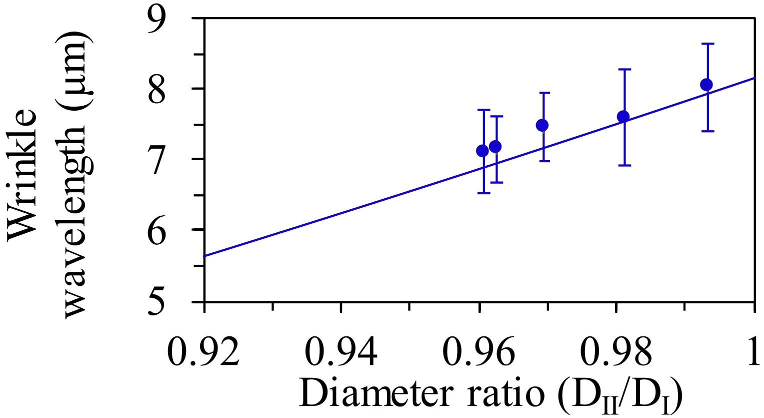


D(V)/DI~1 (V=2.85kV)





$D(V)/D_I$=0.96 (V=0kV)

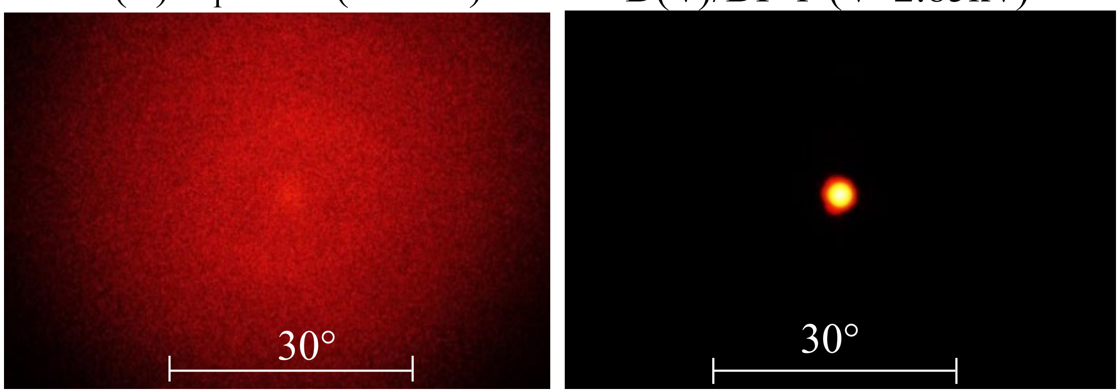


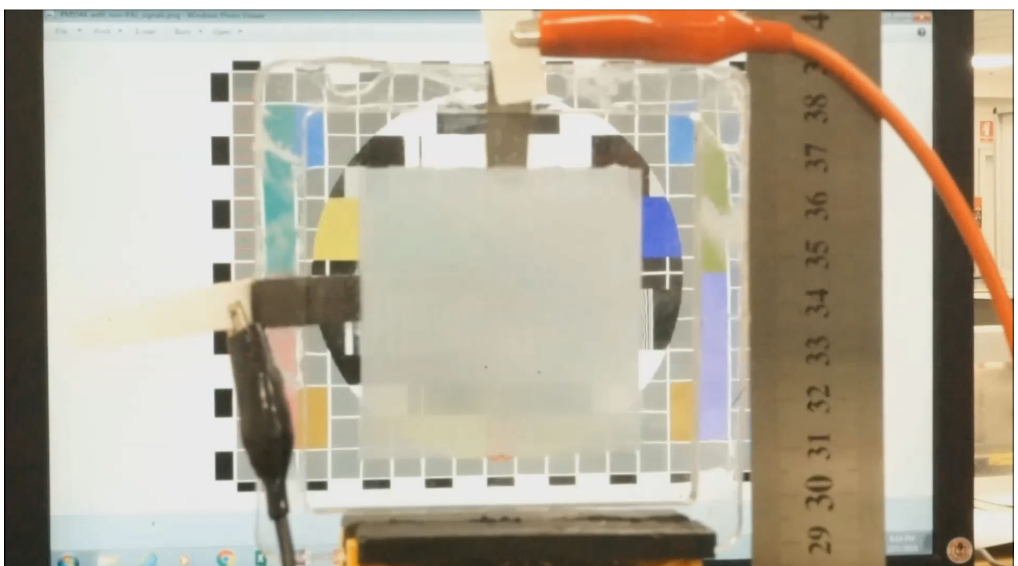
Results: Tuning transparency by DEA activation

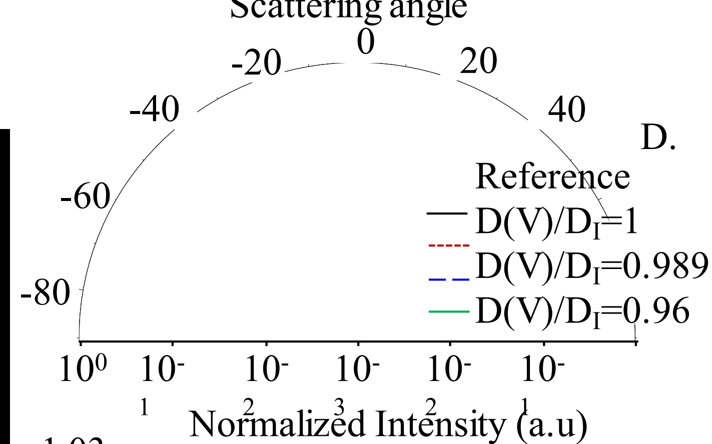
- The wrinkled surface scatterers the light (full width at half-maximum angle = 44.77°)
- Tunes transparency from 1.8% transmittance to 81% upon activation (involves only 4% compression strain).

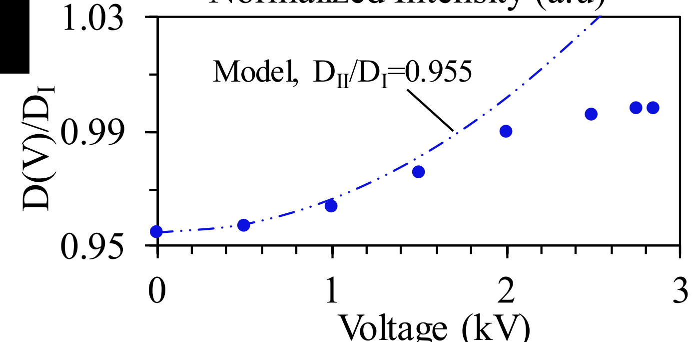
Light Scattering

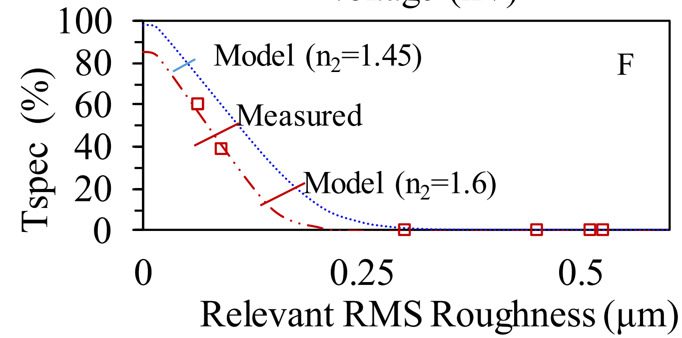
$D(V)/D_I$=0.96 (V=0kV) D(V)/DI~1 (V=2.85kV)





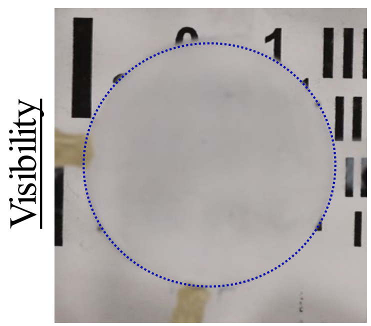




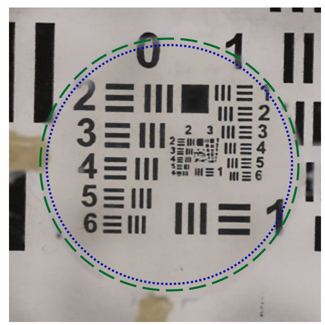


Device Performance and Reliability

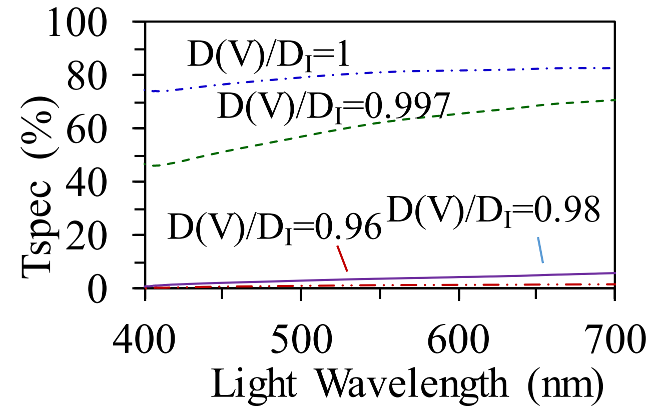
- The transparency tuning is broadband (i.e. throughout visible range)
- Consumes very low power 0.81W/m^2 (2.85kV and <1μA)
- Reliable for repeated and long hour activations

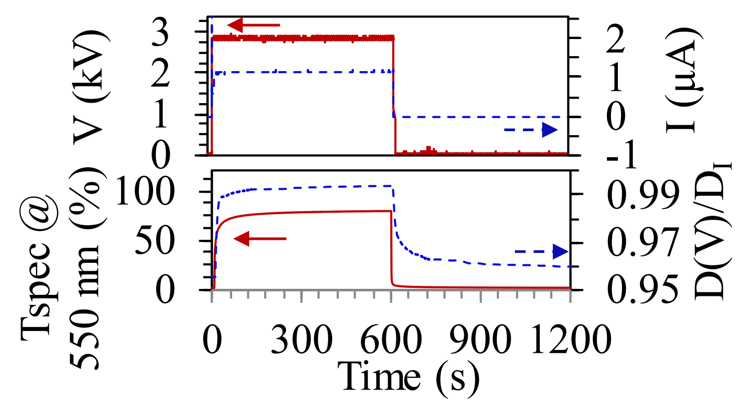


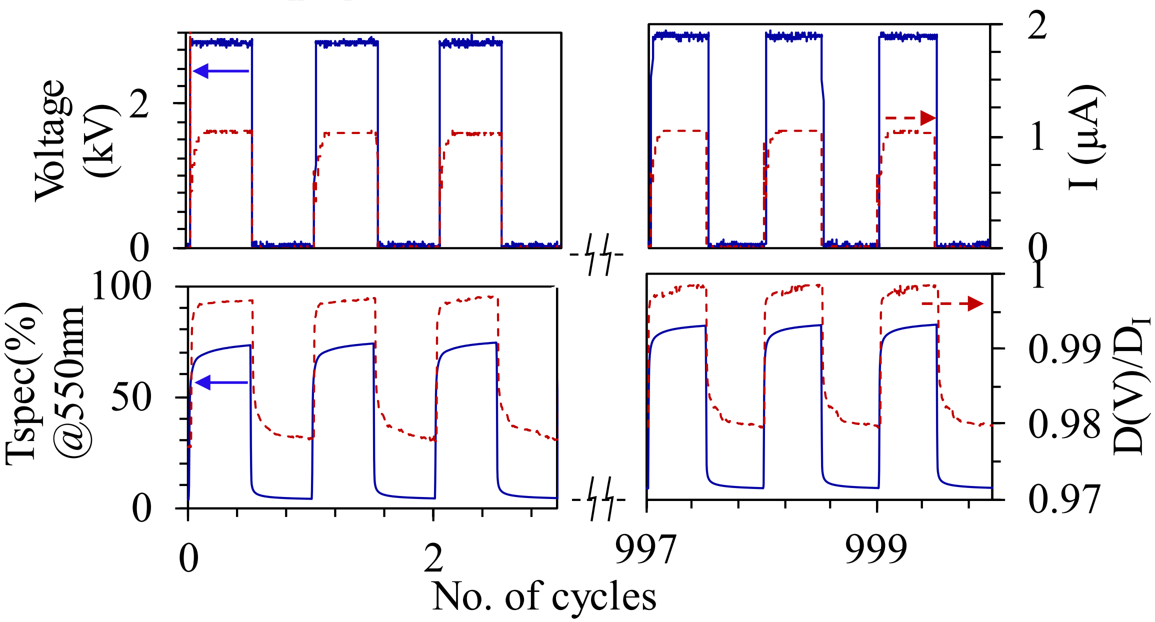
$D_{II}/D_I = 0.96$

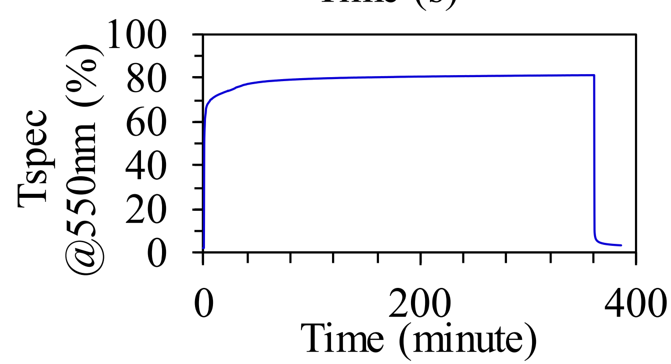


$D(V)/D_I \sim 1$







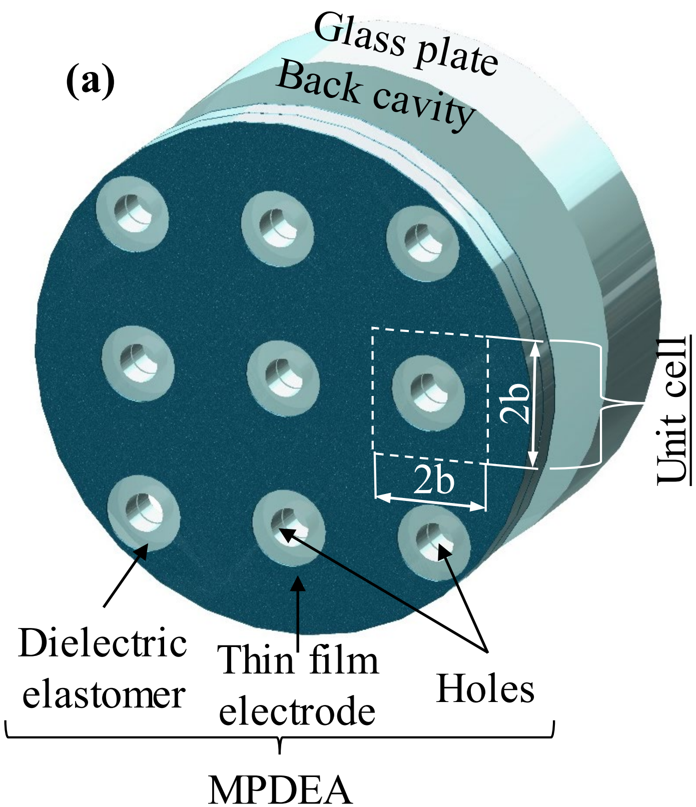


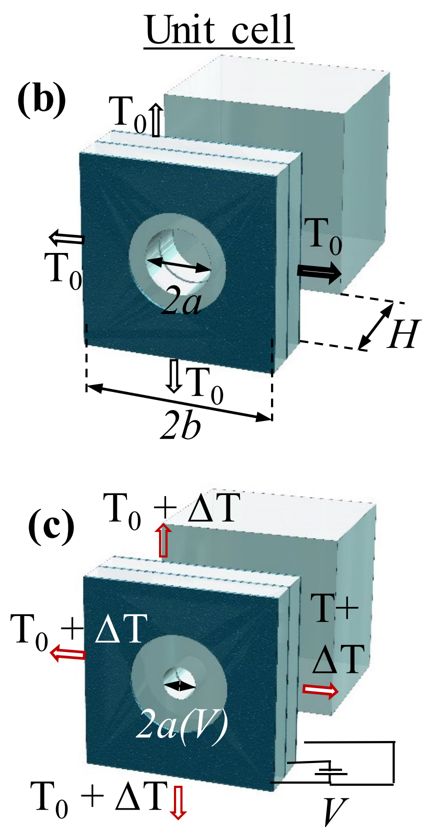
Part II
Tunable Micro-Perforated Membrane Absorbers

- **Problem Summary: Fixed absorption spectrum of Narrow Bandwidth**
- **Proposed Solution: DEA-based tunable microperforated membrane absorbers (tunable broader absorption spectrum)**

Proposed Solution: Tunable MPDEA Absorber

- MPP's absorption frequency depends on perforation size and membrane tension





Resonant Frequency assuming Helmholtz Resonator

$$f = \frac{c}{2\pi}\sqrt{\frac{\pi a^2}{(2b)^2 . H . (2h)}}$$

where, c is velocity of sound

Voltage induced stress change

$$\Delta\sigma_1^{\infty} = -\frac{\nu P_e}{1-\nu}.$$

where, $P_e = \frac{\epsilon_r \epsilon_o \left(\frac{V}{t}\right)^2}{2}$ electrostatic pressure, ν is the elastomer's Poisson's ratio, V is the applied voltage and t is the membrane thickness, ϵ_o is the vacuum permittivity, ϵ_r is the dielectric constant.

Voltage induced reduction in hole radius

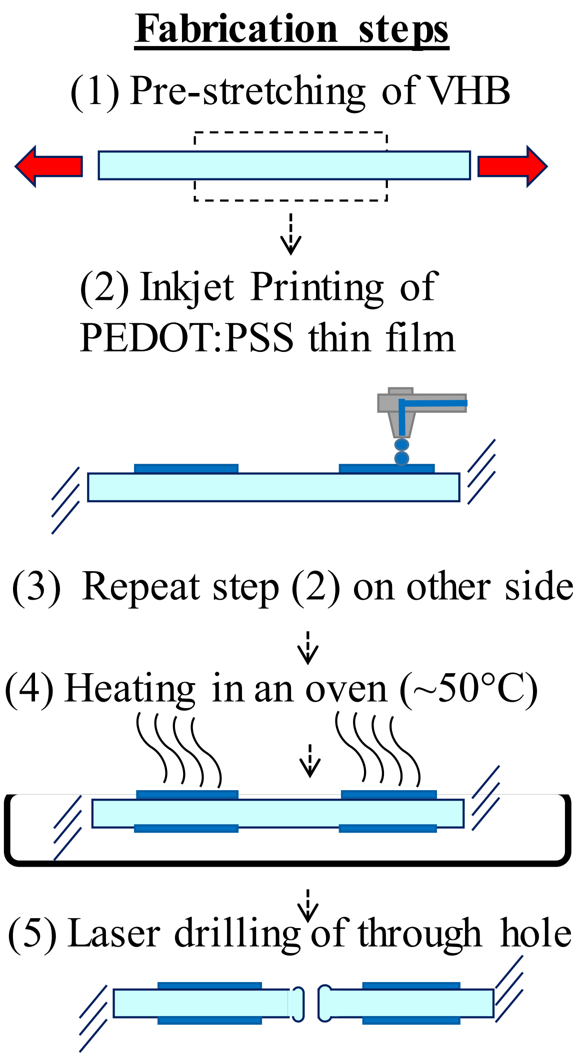
$$\Delta a(V) = \frac{\nu}{1-\nu}\frac{P_e}{E}\left[b + \frac{a^2}{b} - 2a - \nu\left(b - \frac{a^2}{b}\right)\right]$$

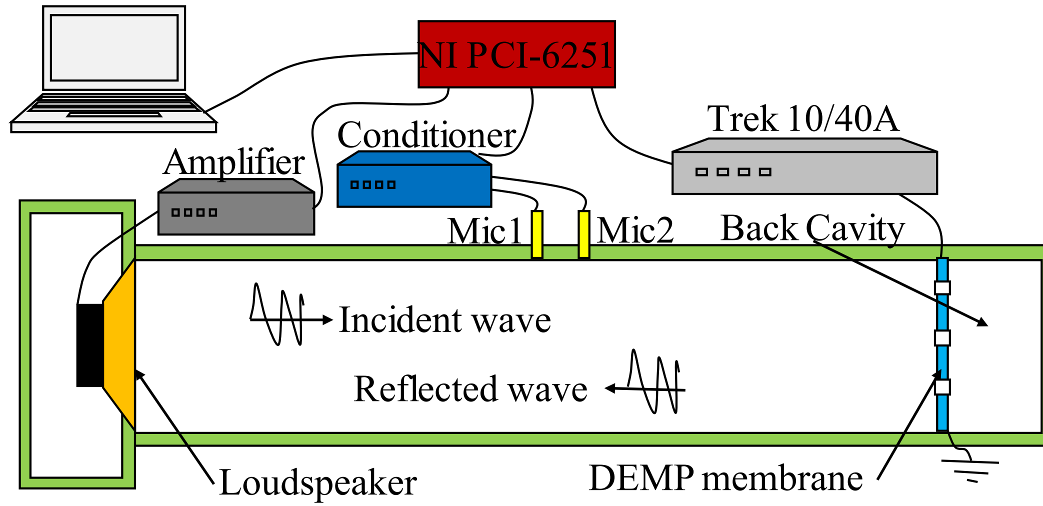
- Absorption spectrum of an microperforated membrane absorber is modeled by Maa et. al. and Y. Li et. al. *

*Li, Y., & Assouar, B. M. (2016). Acoustic metasurface-based perfect absorber with deep subwavelength thickness. *Applied Physics Letters*, *108*(6), 063502.

** Lu, Z., Shrestha, M. & Lau, G.-K. Electrically tunable and broader-band sound absorption by using micro-perforated dielectric elastomer actuator. *Applied Physics Letters* **110**, 182901, doi:10.1063/1.4982634 (2017).

Experiment



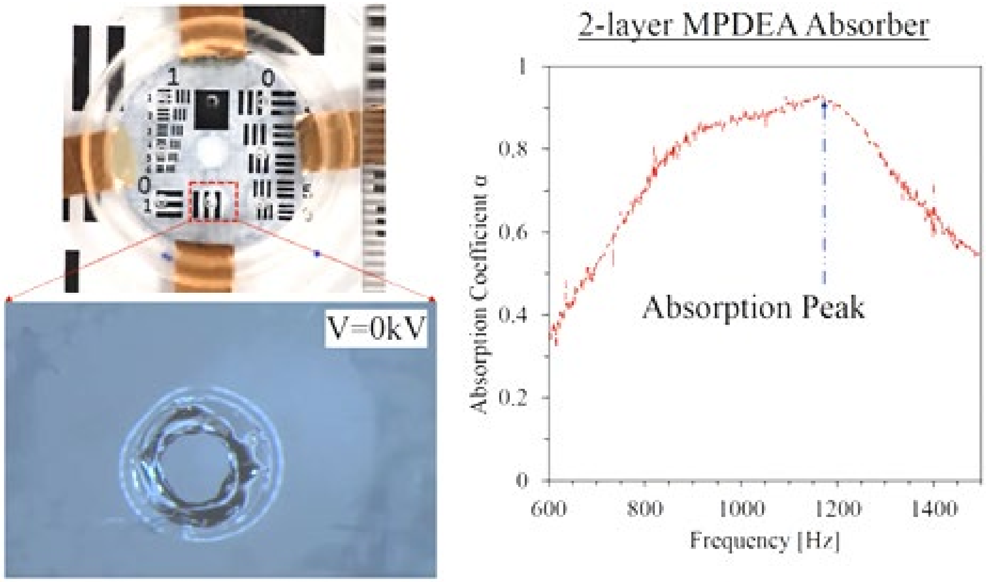


- Impedance Tube (770mm long) Setup used to characterize absorption property of cavity backed resonant absorber
- Two microphone method used
- Microphone switch method used for phase and amplitude correction

Transparent Tunable MPDEA Absorbers

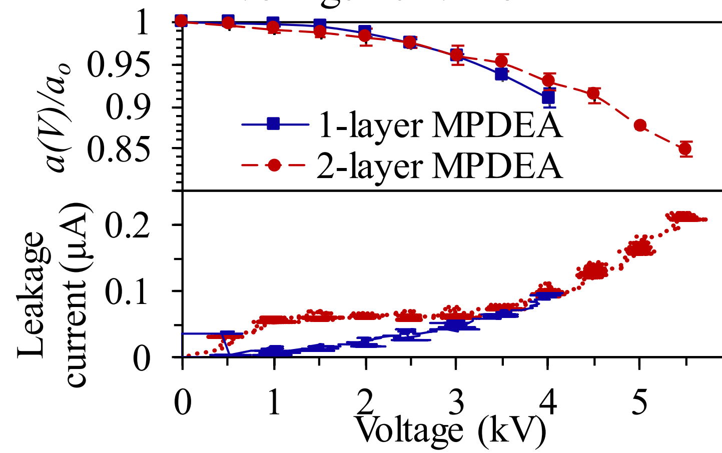
- 2-layered MPDEA were ~70% transparent
- Hole diameter reduced by >15% at 5.5kV

- Absorption Bandwidth at α=0.8 is 444Hz from 846Hz-1290Hz
- Resonant Frequency is shifted from 1170Hz to 992Hz upon activation

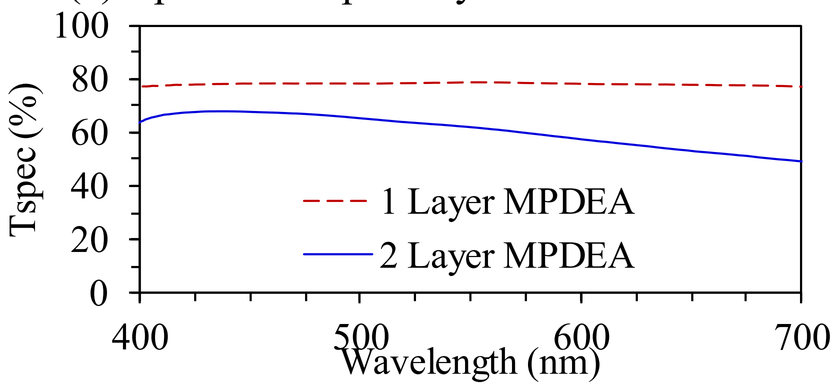


Voltage ramp up to reduce hole size and shift absorption peak

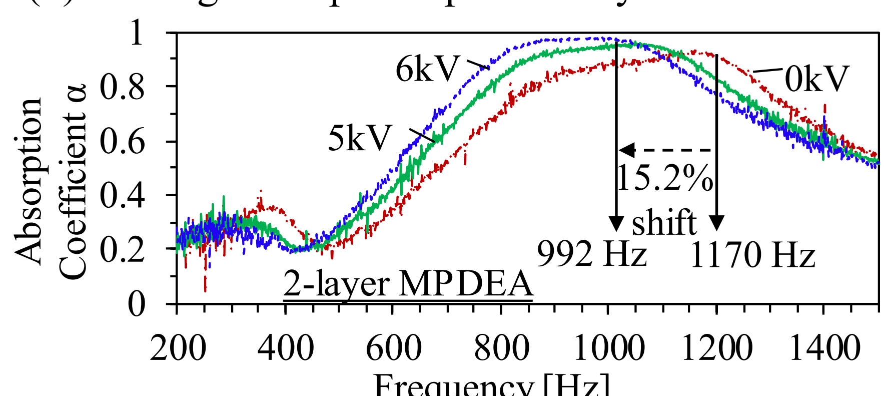
(b) Perforation diameter reduction by DEA voltage activation



(c) Optical transparency of the absorbers



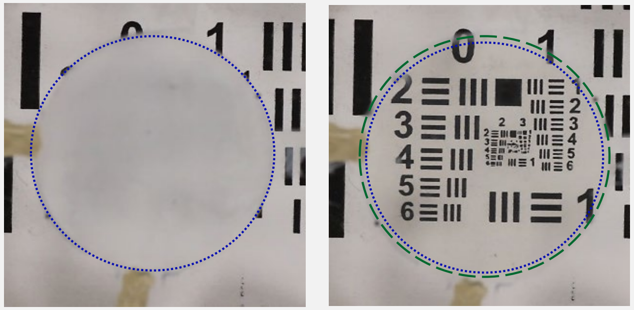
(d) Shifting absorption spectrum by DEA activation



Conclusions

Transparency Tuning Using DEA

- High performance, low cost transparency tuning device based on surface wrinkling with TiO_2/PEDOT:PSS transparent coating layer
- Electrically transparency is tuned from 81% to 1% with less than 5% in-plane radial compression is obtained using DEA



V=0kV V=2.85kV

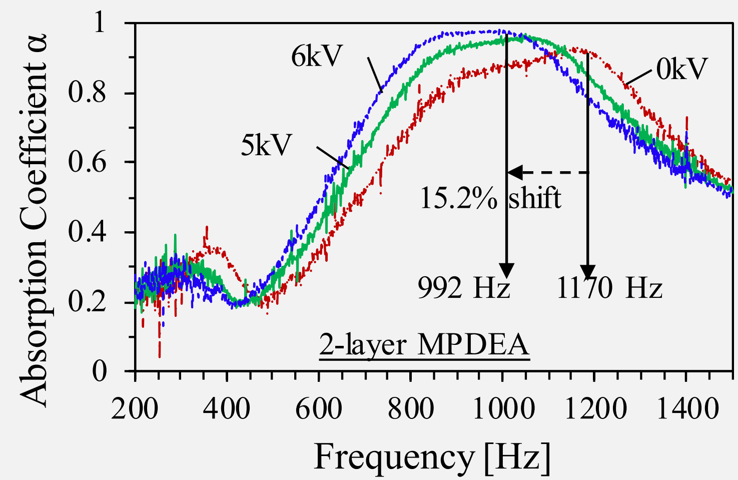
Comparison with Existing Technology

Smart window	Substrate	T_{spec} @550nm	Response time	Power	Sale price on 2016 (brand)
Electrochromic (WO3 and NiO)	Glass	5%-65%	300sec ($5x20\ cm^2$)	0.1-0.5 Whr/sq.m	$1000/sq.m (View glass)
Polymer dispersed liquid crystal	Polymer composite	6%-62%	500 ms	5-20 W/sq.m	$396/sq.m (sonte) $100-300 (Alibaba)
Suspended Particle Device	Glass	2.4%- 59%	100-200 ms	1.9-16 W/sq.m	-
This work	VHB 4905	1%-81%	<60sec	0.831 W/sq.m	~$65.6/sq.m

Conclusions

Transparent Tunable Acoustic Absorber

- Broader band absorption is obtained by micro-perforated DE absorber
- Peak-frequency is tuned by DEA (by 178Hz from 1170Hz)
- PEDOT:PSS/Triton-x100 is inkjet printed to make transparent compliant electrode



Comparison with Existing Technology

Acoustic absorber	Material and form	Back-cavity depth	Clarity	Bandwidth for (α>55%)	Maximum α at resonant frequency
Absorber Light Curtains	Polyster Fibre weave	150mm	Frosted	590Hz (from 400 to 890Hz)	68% at 629Hz
Microperforated Glass	Microperforated glass panel	25mm	Clear	578Hz (from 500 to 1078Hz)	94.8% at 780Hz
This work	Microperforated VHB membrane	40mm	Clear	800Hz (from 621 to 1421Hz)	97.4%@ 934Hz

Recommendations for Future Work

- Window appliances desire a lifetime of 20 to 25 years
  - Currently used elastomer is not weatherproof
  - It can creep and tear over time
  - Investigate new weatherproof dielectric elastomer materials
- High voltage requirement can be concerned
  - Experiment on soft dielectric materials with high dielectric constant
- Current tunable MPDEA absorber is working in the low-to-medium frequency
  - R&D on mass-loaded membranes to target low-frequency
- Large back-cavity depth of current absorber
  - R&D backed-cavities with meta-surface to reduce cavity depth

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Thank You

Questions are Welcome