Effect of Intensity and Wavelength of Spectral UV Light on Discoloration of Laminated Glass/EVA/PPE PV Module

Polymeric Materials Group

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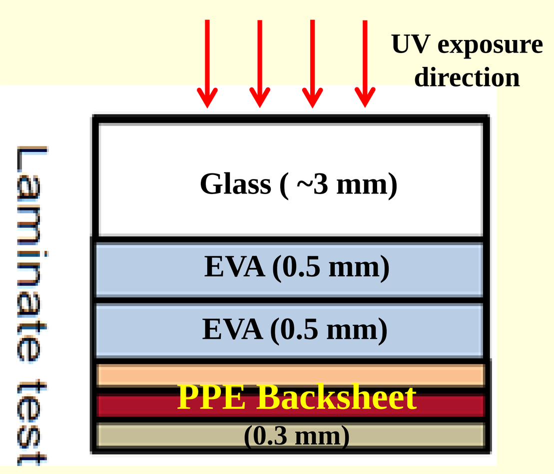
Introduction

Discoloration, one of major failure modes of PV modules, could result in lower efficiency of power output and cause concerns for long-term durability. Studies have indicated that ultra-violet (UV) irradiation is a predominant environmental factor for yellowing occurred in PV modules. However, the quantitative effects of light intensity and wavelength on the discoloration of modules are still unclear.

This work aims to establish a quantitative relationship between the spectral UV irradiance/wavelength and the discoloration of a laminated Glass/EVA/PPE system during UV exposure at elevated temperature. The yellowing mechanism of the model system has been investigated, and the validation of the reciprocity law has been carried out. The dependence of yellowing on wavelength (i.e., action spectrum) has also been established. This study provides foundations for developing accelerated laboratory testing and mathematical models for service life prediction.

Experiments

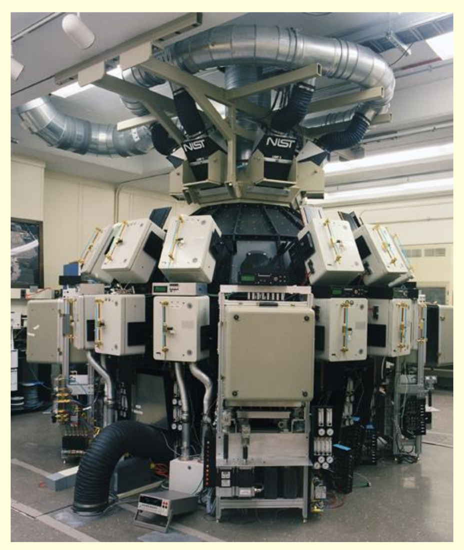
Sample Construction

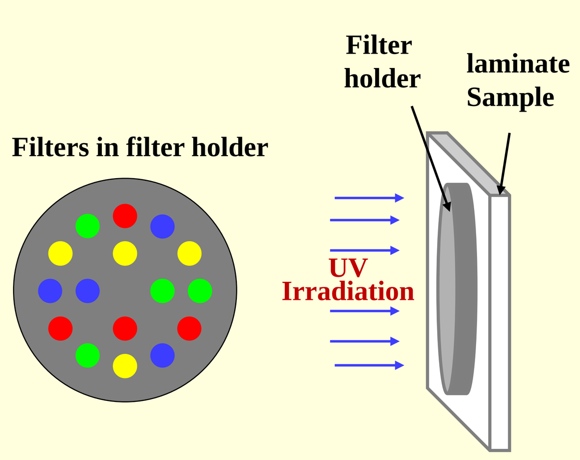


Large samples to avoid the edge effect on yellowing data

Exposure conditions

NIST 2-meter SPHERE*



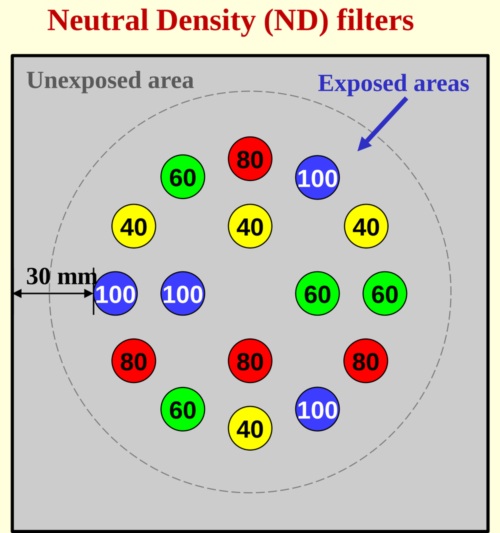


- T = 85 ± 5 °C
- RH = 0% with precision of 1 % (Dry)

* *Chin et al, Review of Scientific Instruments (2004), 75, 4951; Martin and Chin, U.S. Patent 6626053.*

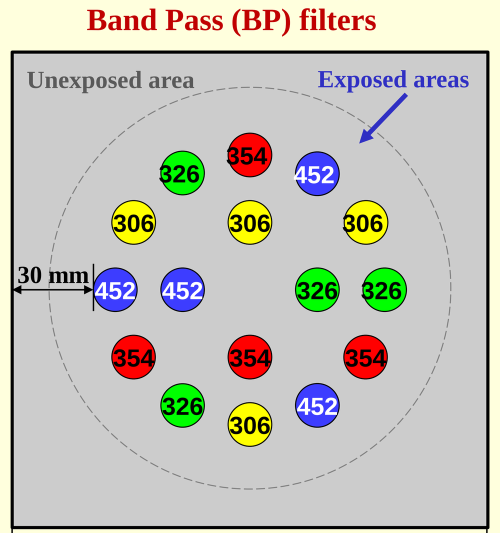
Experimental design

1) Reciprocity Study: Neutral Density (ND) filters



Various intensities of 40 %, 60 %, 80 % and 100 % (with no filter)

2) Wavelength Study: Band Pass (BP) filters



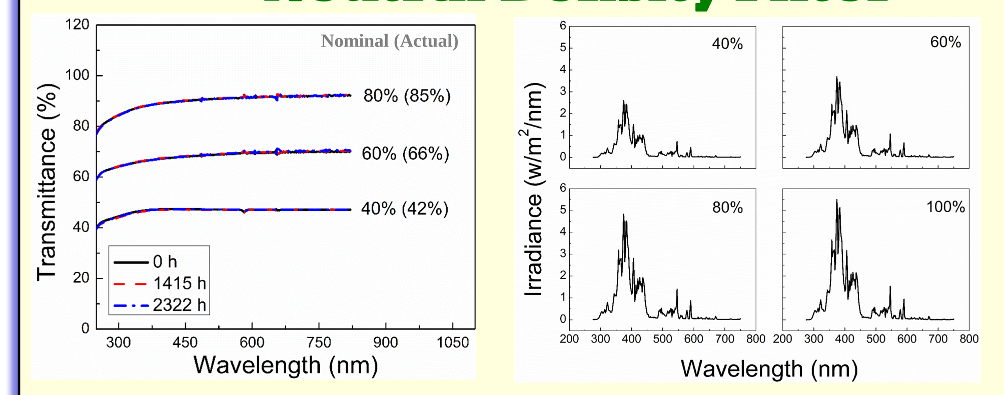
Various wavelength ranges centered at 306 nm, 326 nm, 354 nm and 452 nm

Characterizations

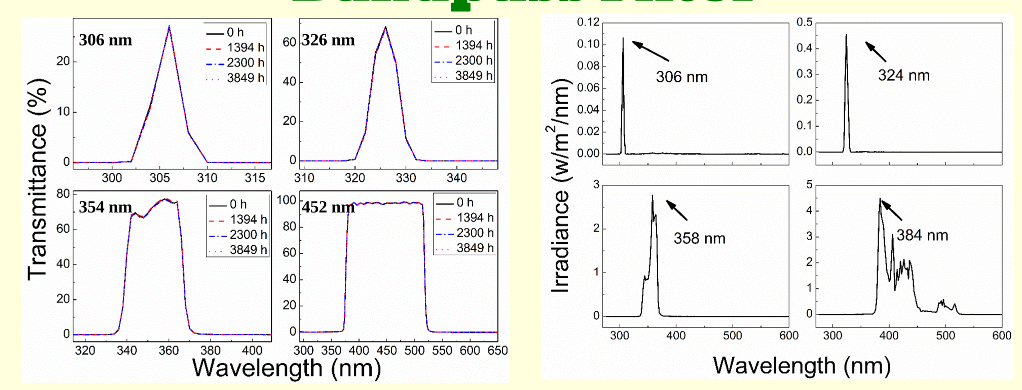
- Digital photos
- UV-Visible spectroscopy in reflection mode

Stability of Filters and Spectral Distribution

Neutral Density Filter



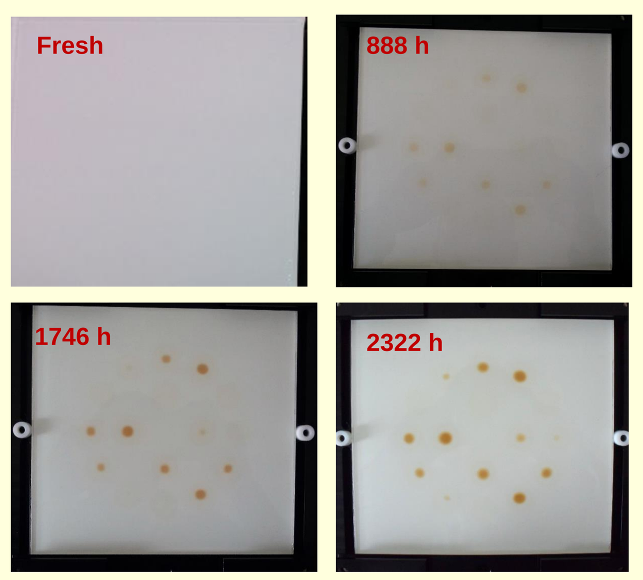
Bandpass Filter



➢ Both neutral density filters and bandpass filters are stable during UV exposure at 85°C/Dry on the SPHERE.

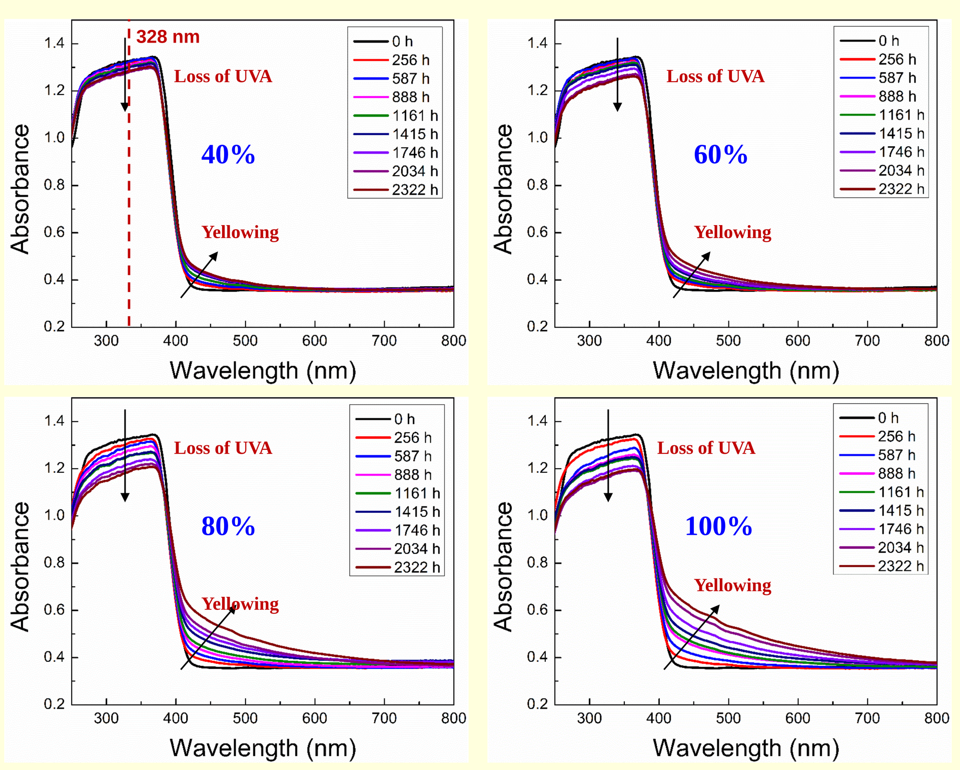
Effect of UV Light Intensity (Reciprocity study)

Digital Photos



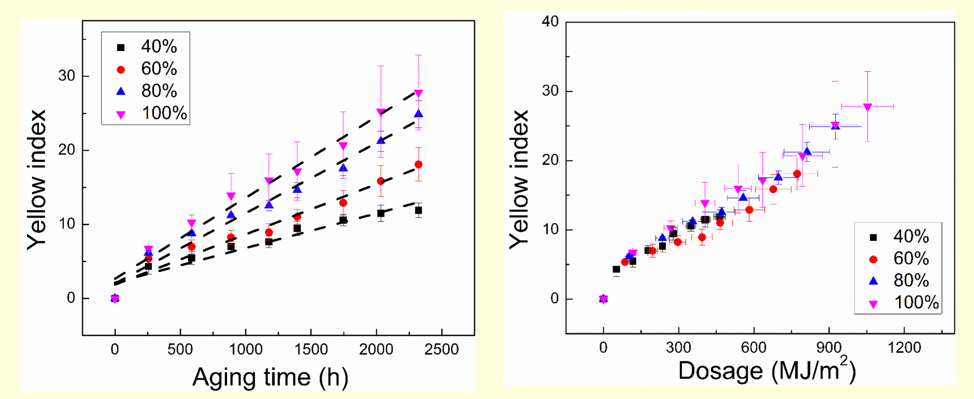
➢ The exposure regions gradually became yellow, while yellowing areas basically kept constant.

UV-Visible Spectra



➢ The loss of UV absorbers (UVA) correlated with the yellowing.
➢ Optical changes at different light intensities have a similar trend.

Evolution in Yellowing Index (YI)



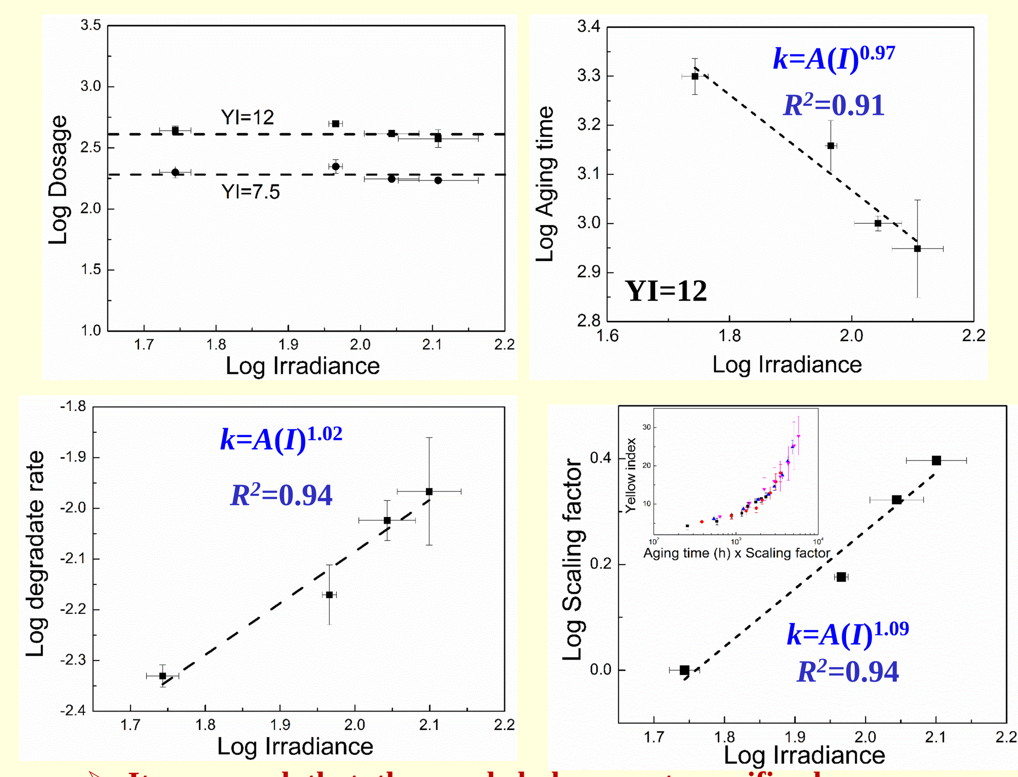
1) A higher light intensity led to a faster yellowing growth.
2) A quasi-linear relationship was observed for the YI-aging time plot.
3) The YI-dosage plots for different light intensities superimposed in to a single master curve.

Validation of Reciprocity Law

Schwarzschild Law: $t(I)^p$=constant or $k=A(I)^p$

When Schwarzschild coefficient p=1, Schwarzschild Law reduced to Reciprocity Law.

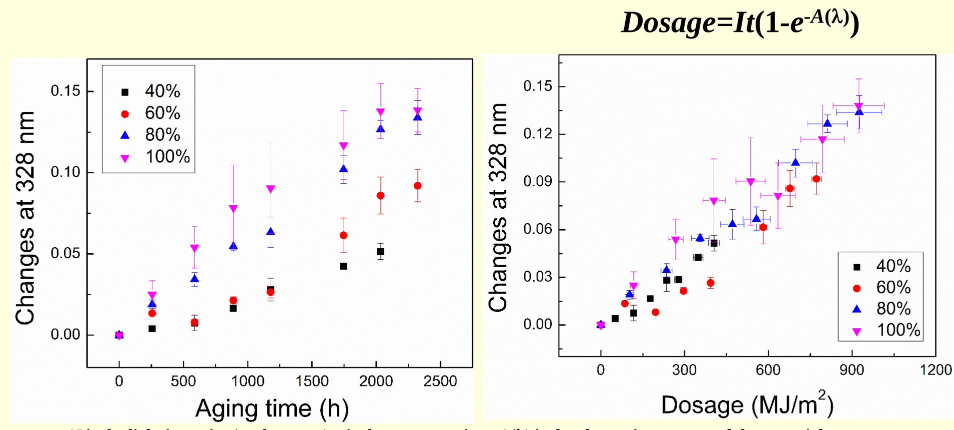
➢ **For YI growth**



➢ It appeared that the needed dosage at specific damage was independent of intensities and p value was close to 1.
➢ It was also found that growth of YI followed the same mechanism with different light intensity, as YI-aging time curves could be superimposed in to a master curve based on scaling factors.
➢ Reciprocity Law appeared to be obeyed.

Evolution in UVA Loss at 328 nm

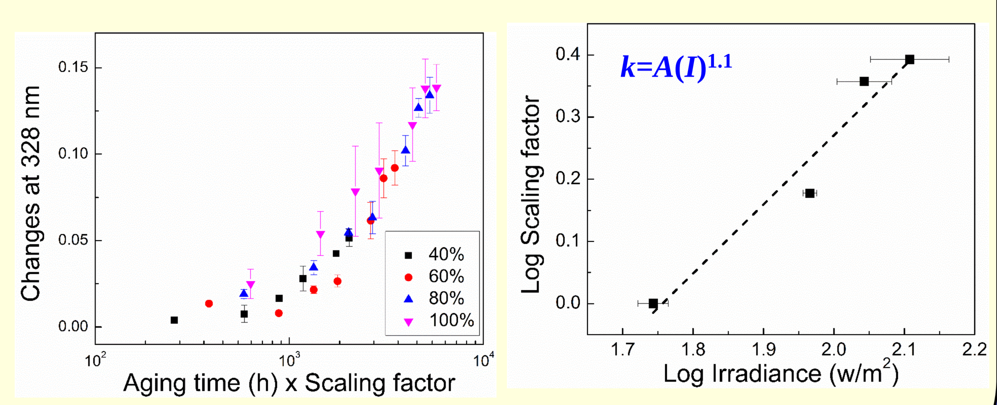
Dosage=It(1-e$^{-A(\lambda)}$*)*



**I is the light intensity (or dose rate), t is the exposure time, A(λ) is the absorption spectra of the materials.*

1) UVA loss increased with longer exposure time.
2) A higher light intensity led to a higher rate per time for the loss of UVA.
3) When plotting absorbance with dosage, deviations became smaller between different light intensities.

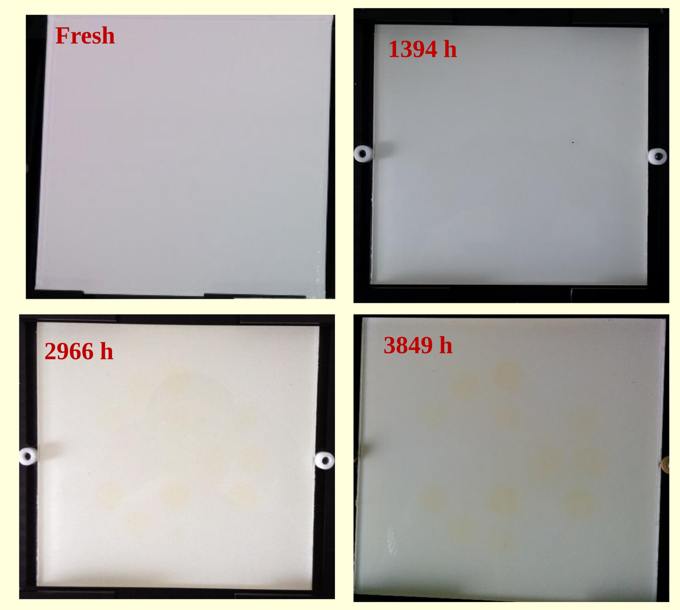
➢ **For UVA loss**



➢ Reciprocity Law appeared to be obeyed.

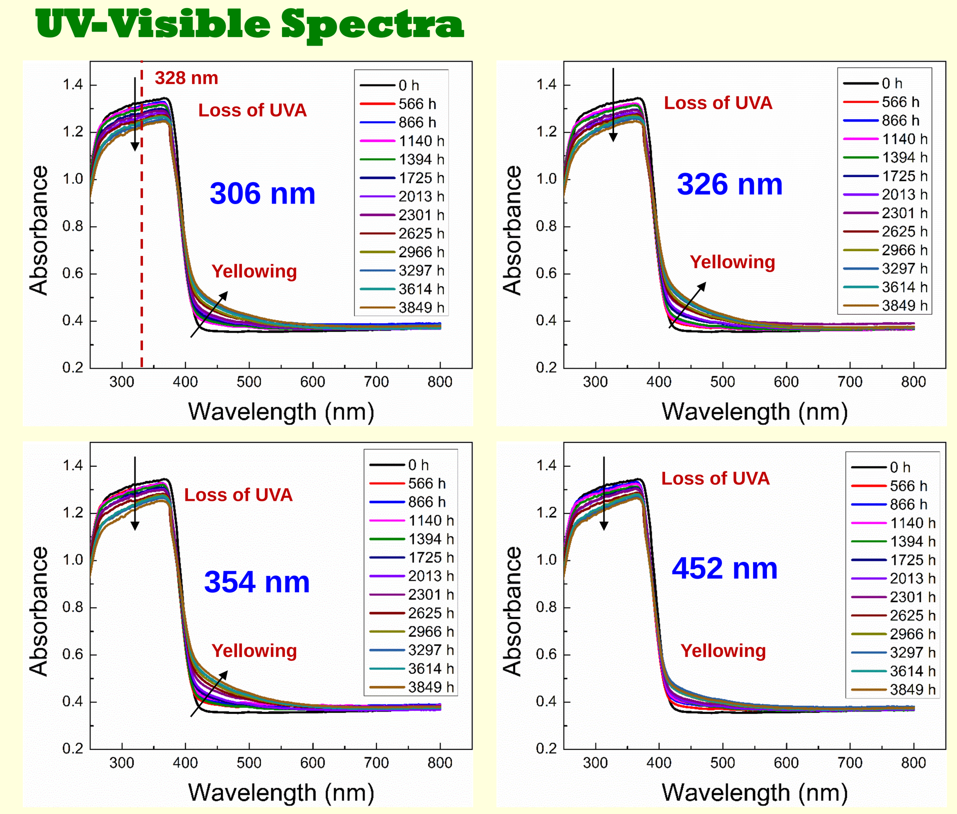
Effect of UV Wavelength

Digital Photos



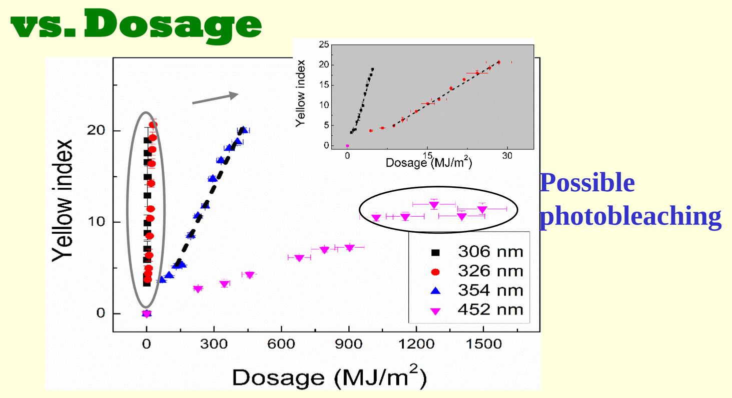
➢ Visible yellowing of regions under 306 nm, 326 nm and 354 nm filters was observed.

UV-Visible Spectra



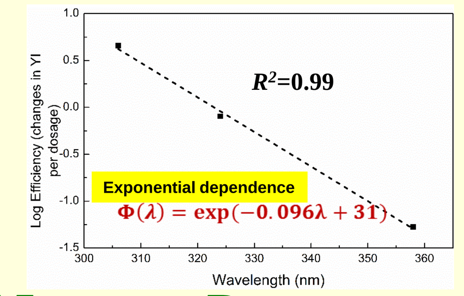
➢ Both UVA loss and yellowing increased with exposure time under wavelengths of 306, 326 and 354 nm.
➢ The growth of yellowing under 452 nm slowed down at late stage, possibly due to competitions between yellowing and photobleaching.

YI vs. Dosage



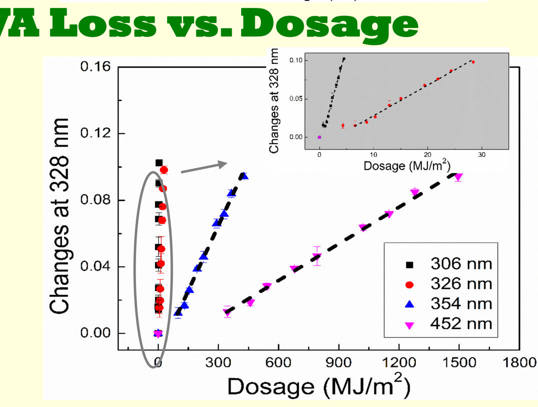
➢ Shorter wavelength led to a higher YI.
➢ YI increased linearly under 306, 326 and 354 nm, while under 452 nm it slowed down at late stage.

Action Spectrum for YI



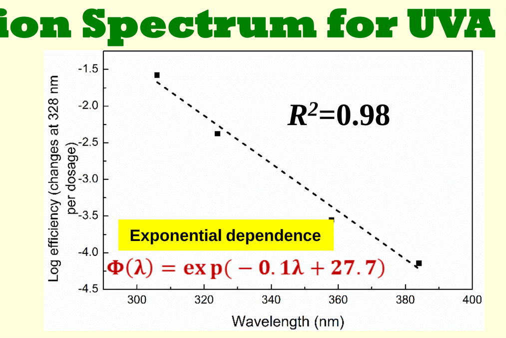
Efficiency was calculated based on yellowing per dosage

UVA Loss vs. Dosage



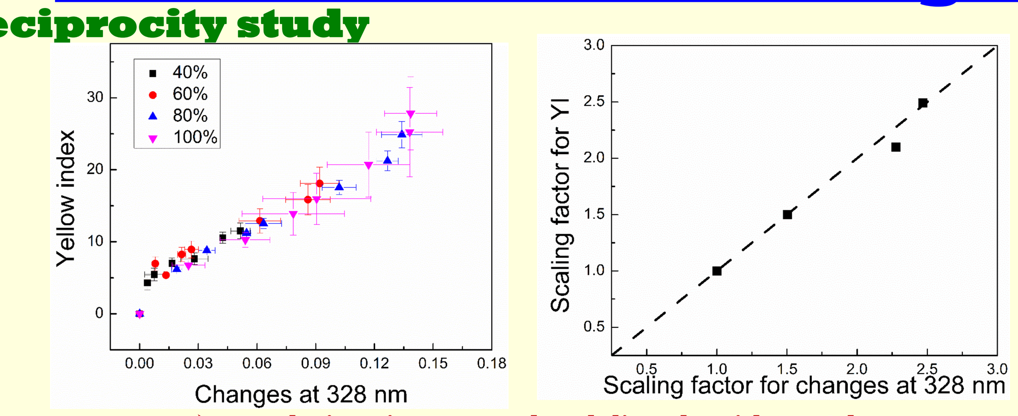
➢ UVA loss increased over UV exposure.
➢ The shorter wavelength, the higher loss rate per dosage.

Action Spectrum for UVA Loss



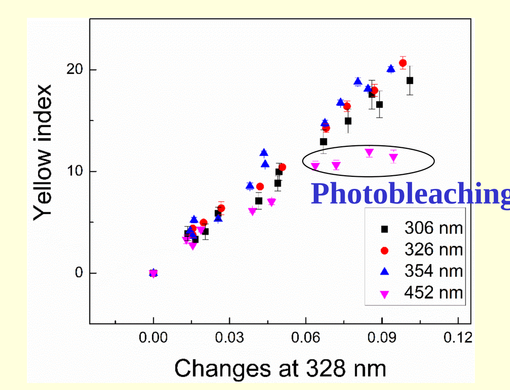
Correlation between YI growth and UVA loss

Reciprocity study



➢ Evolutions in YI correlated directly with UVA loss.

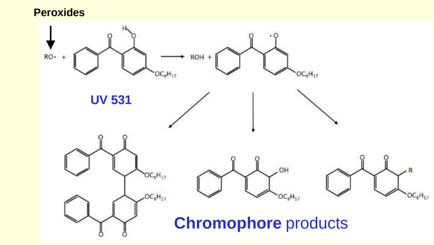
Wavelength study



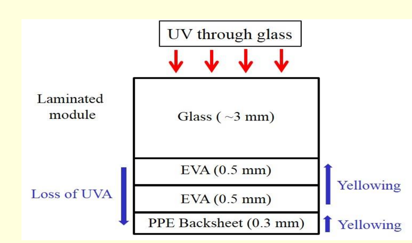
➢ A nearly linear relationship was found between YI and the loss of UV absorbers for the Glass/EVA/PPE system after UV exposure under 306, 326 and 354 nm, but not 452 nm.
➢ Visible light and oxygen, both could contribute to the photobleaching process under 452 nm.

**Decker, J Photochem,1981; Pern. IEEE Photovoltaic Specialists Conference. 1994; Hülsmann, P et al.. Prog Photovoltaics, 2014*

Possible Mechanisms for UVA Loss and Yellowing



1) UVA loss might give rise to chromophore precursors.



2) UVA loss could permit UV light penetration to a greater extent.

**Klemchuk et al.. Polym degrad stabil. 1997; Fechine et al.. Polym degrad stabil. 2002.*

Summary

- Quantitative relationships between light intensity/wavelength and yellowing of Glass/EVA/PPE system have been established.
- The degradation rates for the growth of YI and the loss of UV absorbers are found to be proportional to the UV irradiance. Reciprocity law appears to be obeyed both for the growth of YI and the loss of UV absorbers in the studied UV irradiance range.
- Wavelength effect is clearly seen for the growth of YI and the loss of UV absorbers. The action spectrum in exponential expression, is also obtained for these changes. Photobleaching effect is observed at longer wavelength under 452 nm.
- The yellowing of the glass/ EVA/PPE system can be resulting from degradation of encapsulant or/and backsheet. It is found that the growth of yellowing correlates well with the loss of UV absorbers.