

# Optical Measuring Methods for Transparent Displays

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# Lighting Environments

Examples of transparent display illumination conditions.

Indoor/Indoor



Showcase/Indoor



Outdoor/Indoor

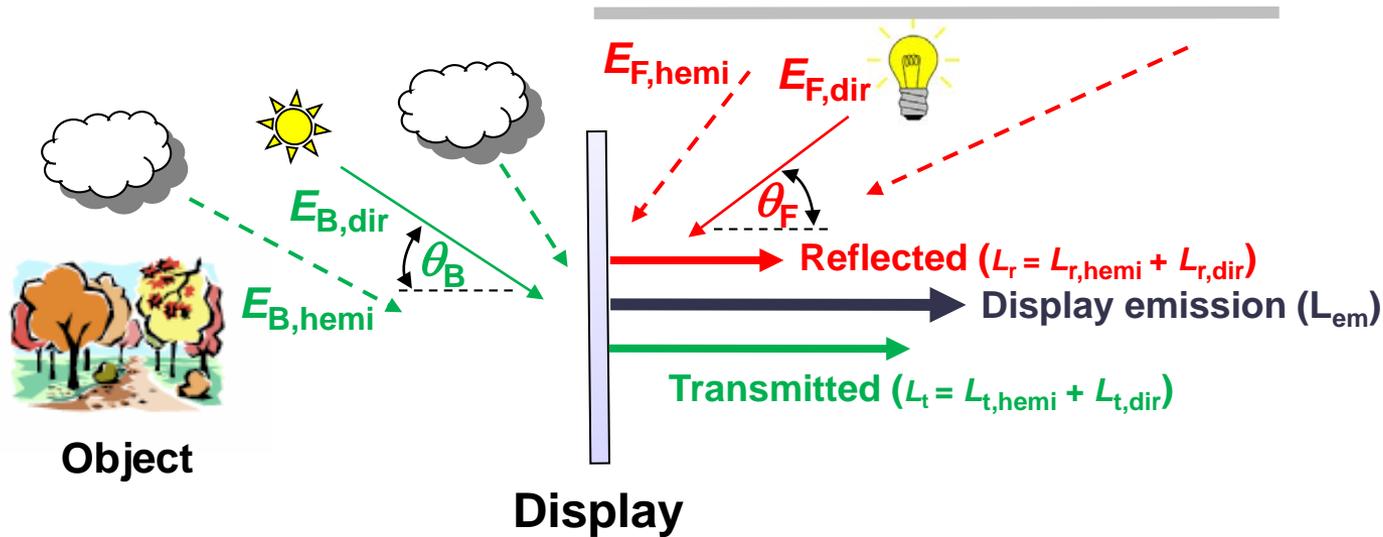


Showcase/Outdoor



# Transparent Display Illumination

Illumination contributions on display:



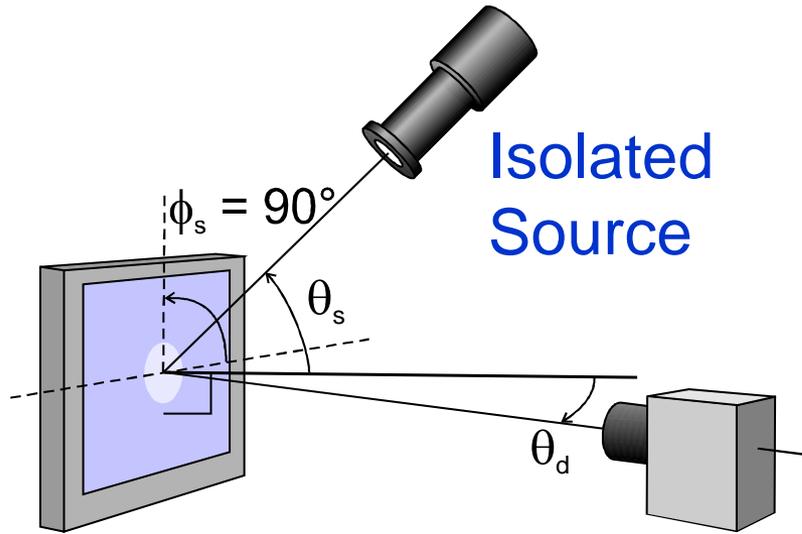
General equation:

$$L_Q = L_{Q,em} + \underbrace{\frac{\rho_Q}{\pi} E_{r,hemi} + \frac{R_{Q,dir}}{\pi} E_{r,dir} \cos \theta_r}_{L_{Q,r} \text{ Reflected luminance}} + \underbrace{\frac{T_{Q,hemi}}{\pi} E_{t,hemi} + \frac{T_{Q,dir}}{\pi} E_{t,dir} \cos \theta_t}_{L_{Q,t} \text{ Transmitted luminance}}$$

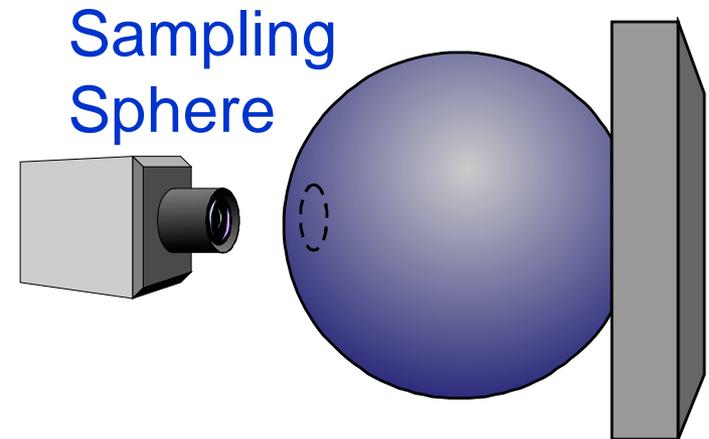
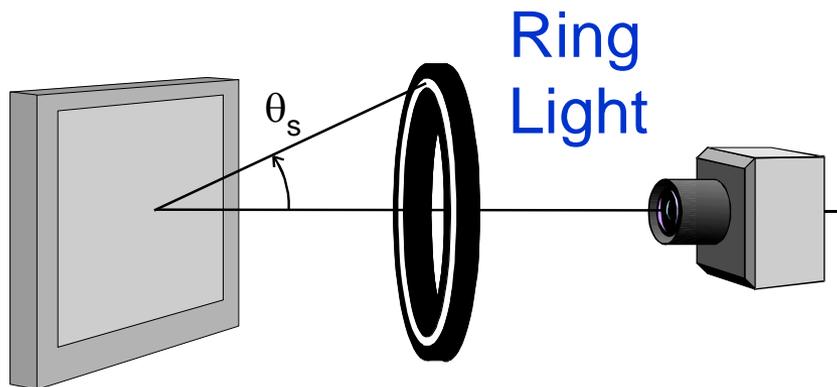
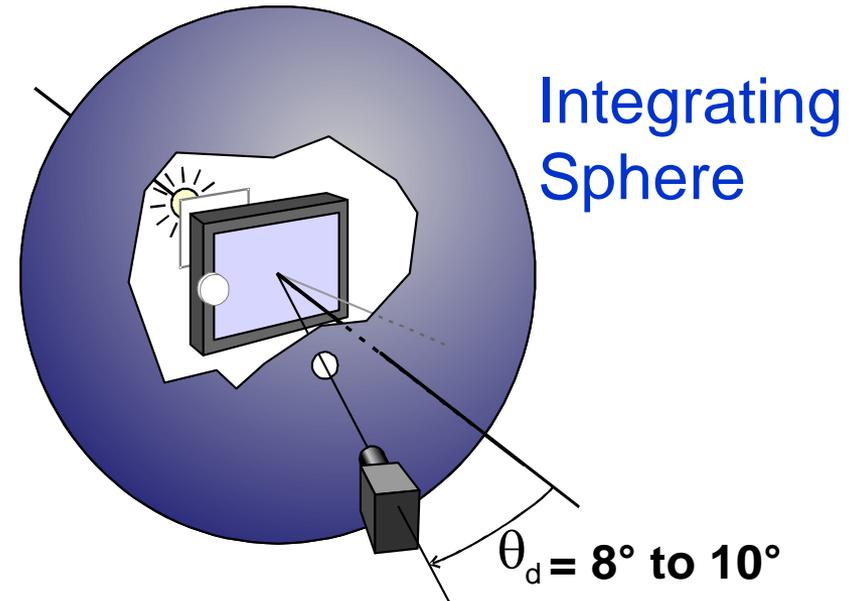
$Q = \text{display color}$

# Hemispherical and Directional Illumination

## Directional Illumination

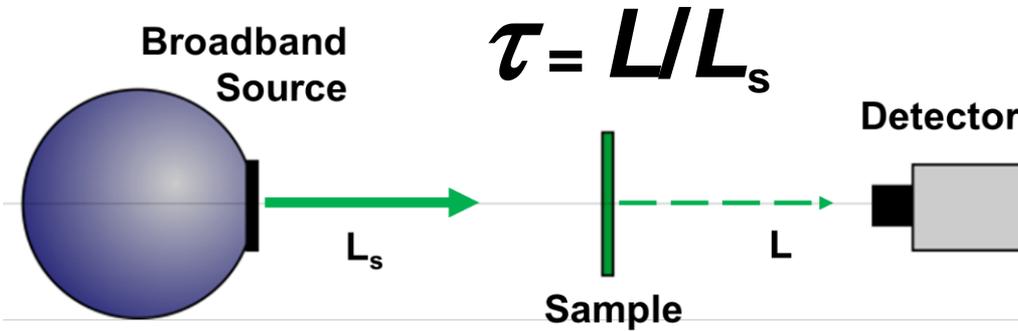


## Hemispherical Uniform Diffuse Illumination

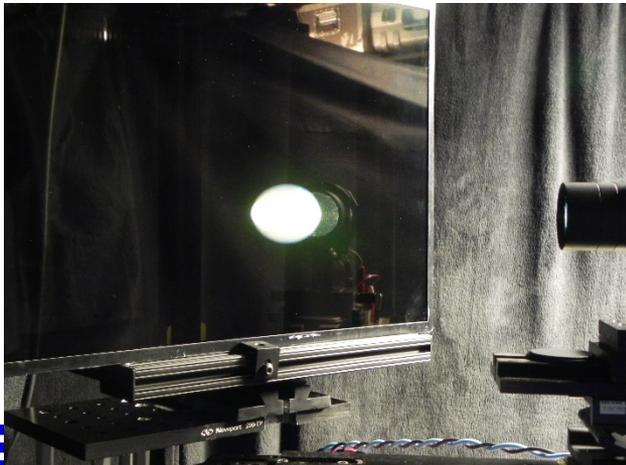


# Regular Transmittance & Reflectance

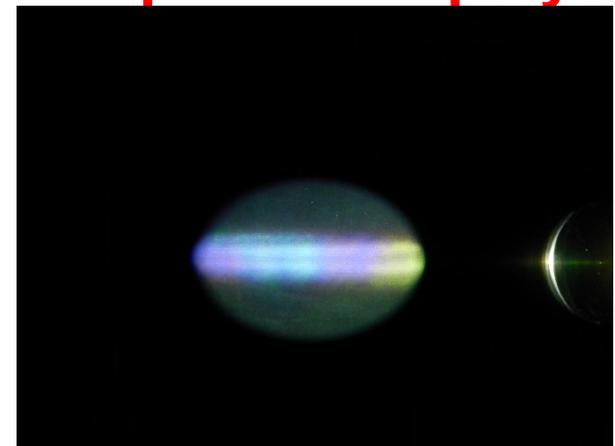
## Standard regular transmittance measurement



## Standard regular reflectance measurement

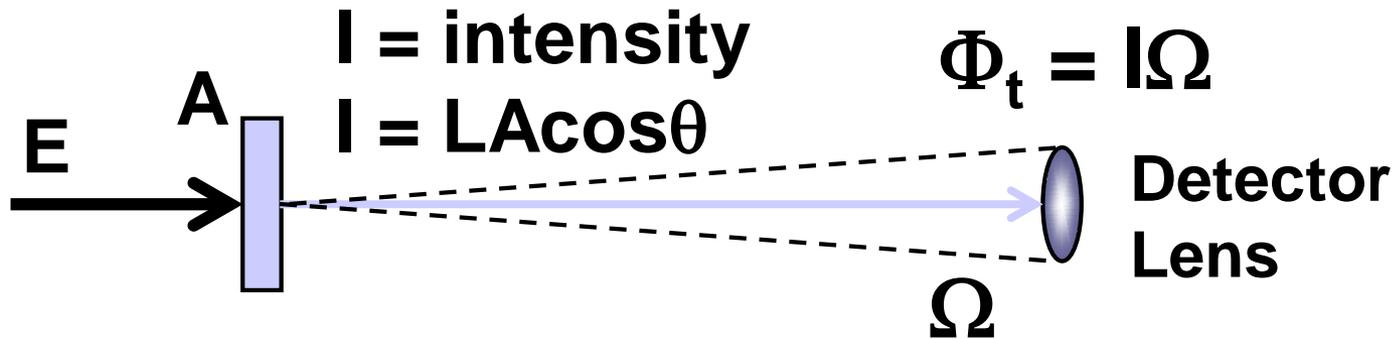


**Problematic for transparent displays.**

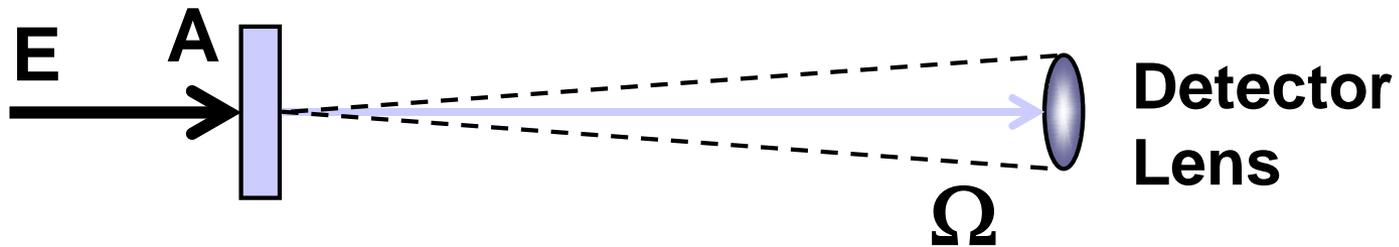


# Transmittance Factor

Transmittance Factor:  $T = \Phi_t / \Phi_p$



Perfect transmitting diffuser:



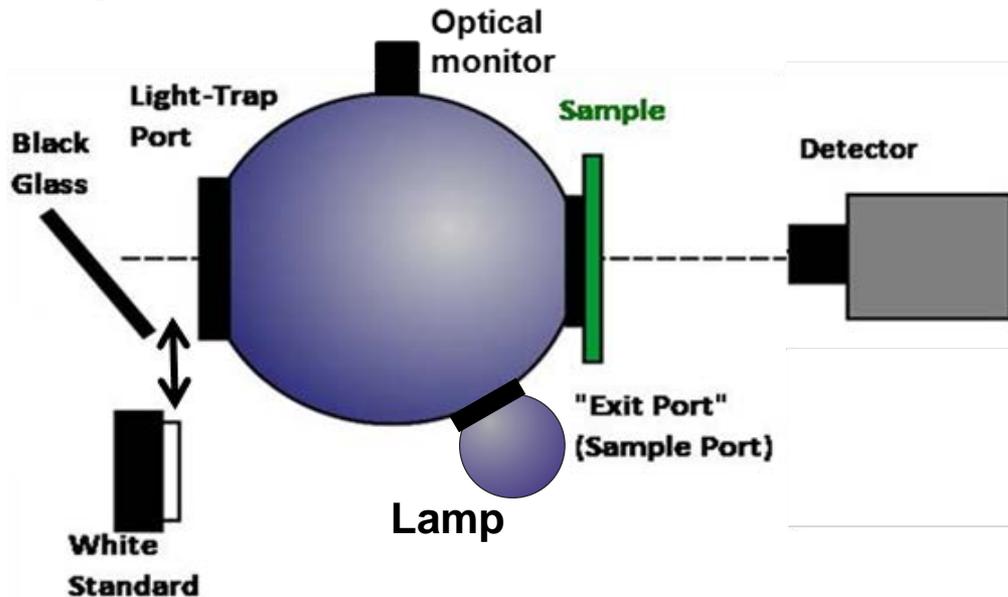
$$I_p = L_p A \cos\theta \quad L_p = E / \pi$$

(Lambertian)

$$T = \Phi_t / \Phi_p = \frac{L A \cos\theta \Omega}{L_p A \cos\theta \Omega} = \frac{\pi L}{E} \quad \left| \begin{array}{l} \text{Specified} \\ \text{Geometry} \end{array} \right.$$

# Hemispherical Transmittance Factor

Realization of hemispherical transmittance factor measurement.  
Adapted from ASTM D1003.



**Regular included**

$$T_{Q,di/0} = \frac{L_{di/0}}{L_s} \cdot \frac{m_{ref}}{m_{di/0}}$$

**Regular excluded**

$$T_{Q,de/0} = \frac{m_{ref}}{L_s} \left[ \frac{L_{de/0}}{m_{de/0}} - \frac{L_{bg} L_{di/0} m_{ref}}{L_s m_{bg} m_{di/0}} \right]$$

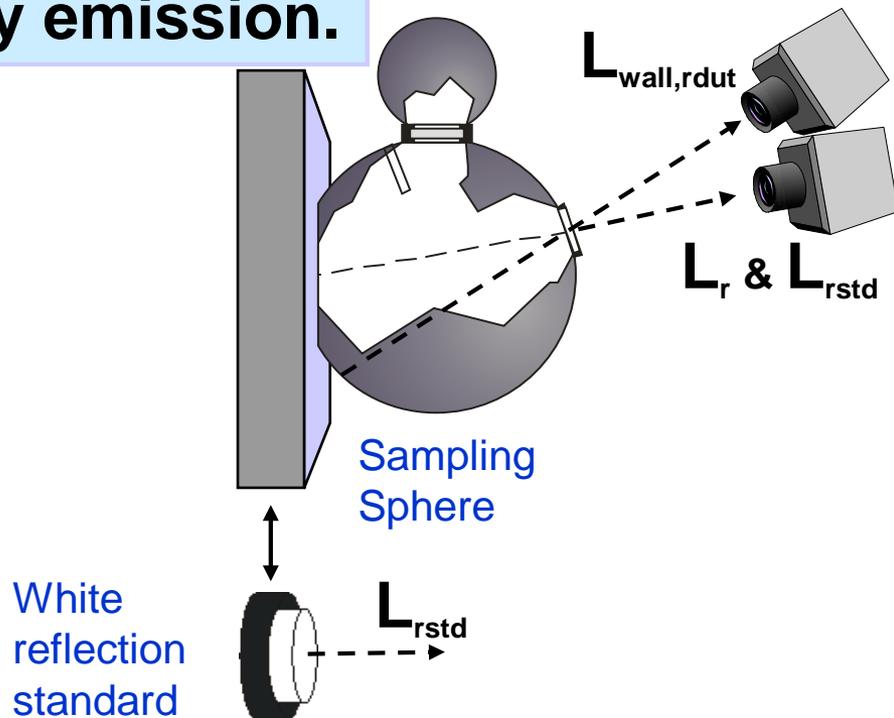
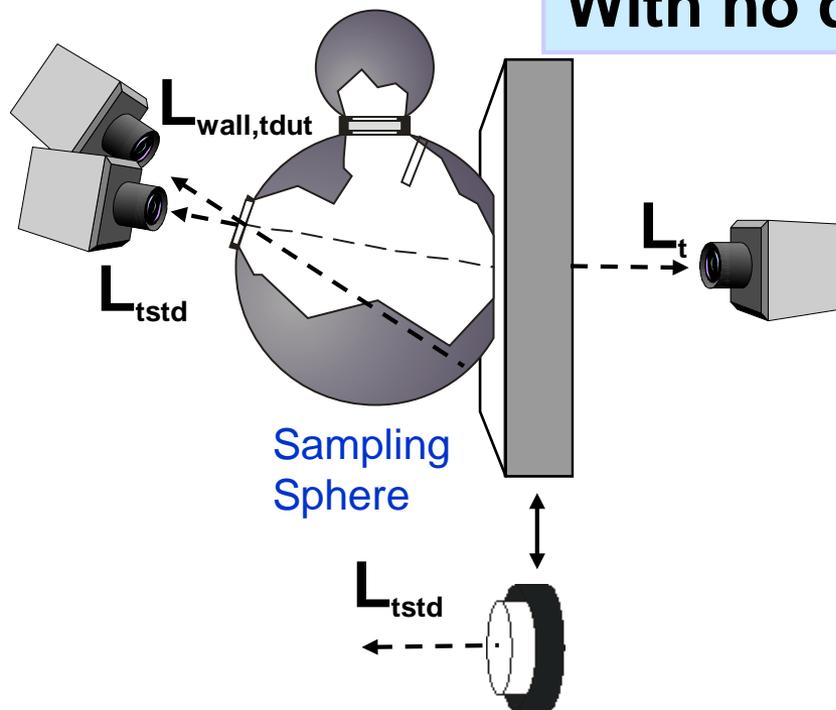
Step	Sample port	Light-trap port	Luminance	Monitor
1	open	white standard	$L_s$	$m_{ref}$
2	sample	white standard	$L_{di/0}$	$m_{di/0}$
3	sample	open	$L_{de/0}$	$m_{de/0}$
4	open	open	$L_{bg}$	$m_{bg}$

# Sampling Sphere Measurements

## Hemispherical transmittance factor

## Hemispherical reflectance

With no display emission.



$$T_Q = \pi L_t / E$$

where  $E = \pi L_{wall,tdut} / R_{wall}$

and  $R_{wall} = R_{std} L_{wall,std} / L_{tstd}$

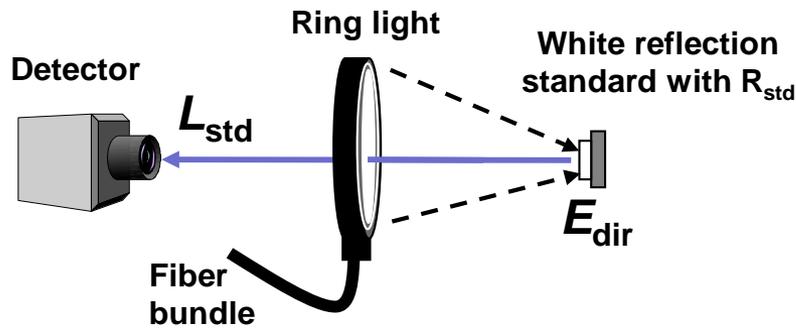
$$R_Q = \pi L_r / E$$

where  $E = \pi L_{wall,rdut} / R_{wall}$

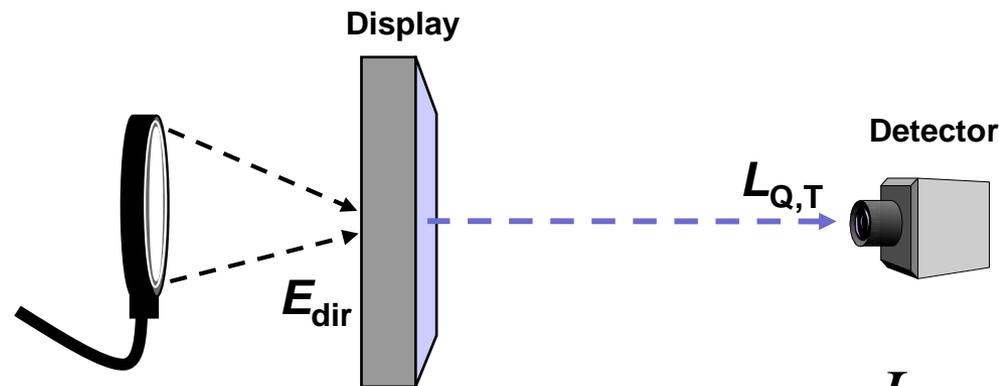
and  $R_{wall} = R_{std} L_{wall,std} / L_{rstd}$

# Directional Transmittance Factor

A ring light was used to simulate directional illumination due to the diffractive scatter of the display.



$$E_{dir} = \pi \frac{L_{std}}{R_{std}}$$



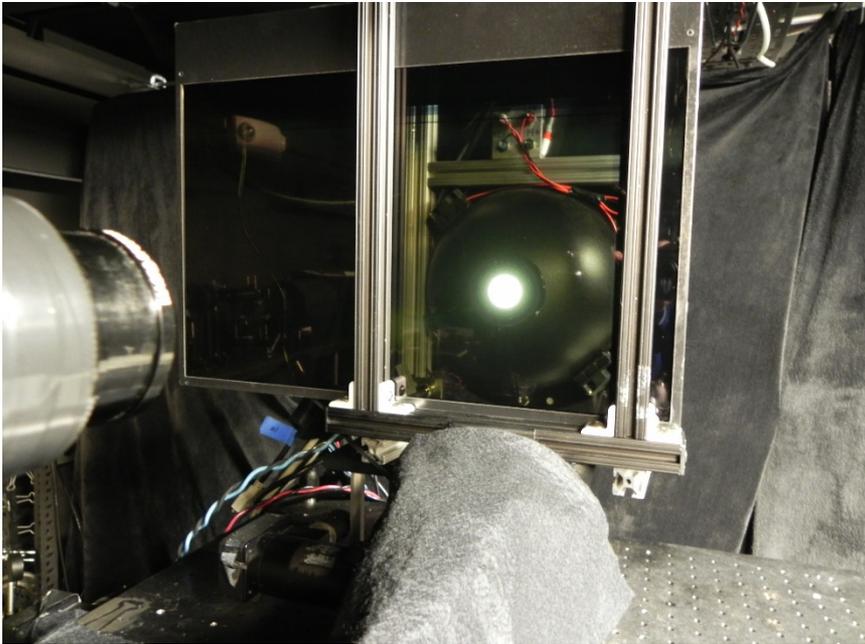
$$T_{Q,dir} = \pi \frac{L_{Q,T}}{E_{dir}}$$

Q= rendered display color

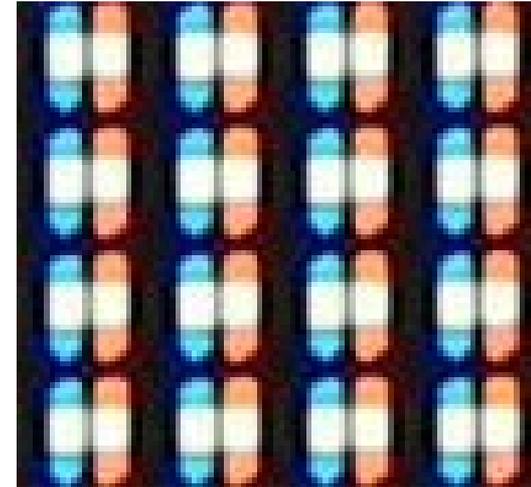
# Transparent LCD Example

Methods were demonstrated using a commercial transparent LCD display.

22" Transparent TN LCD



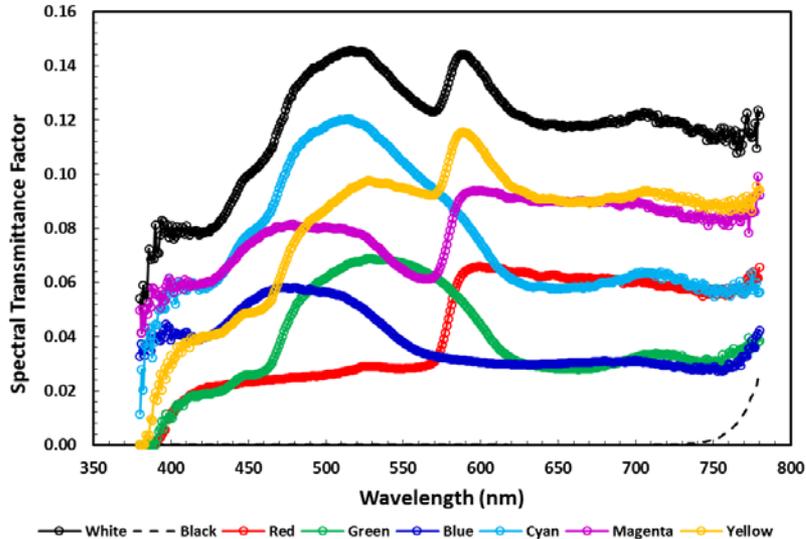
Transparent LCD pixel structure with green pixel off



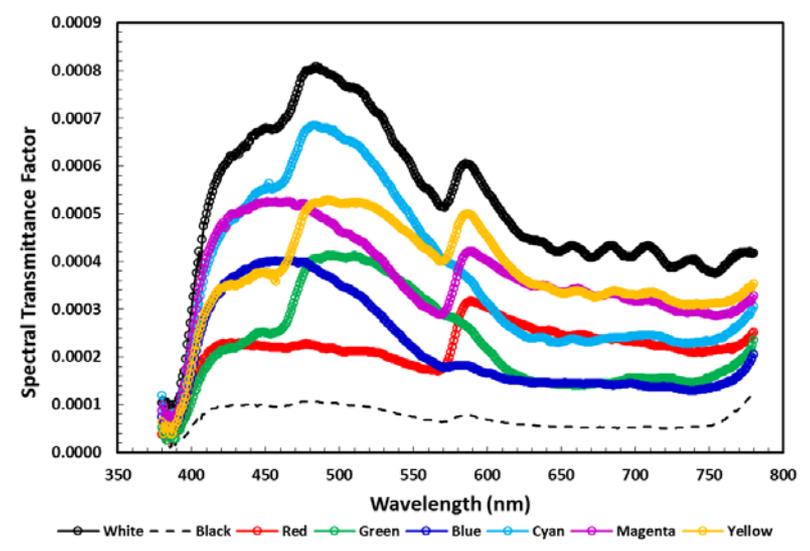
# Transmittance Factor Results

Transmission performance of the transparent LCD display.

## Hemispherical Spectral Transmittance Factor



## Directional Spectral Transmittance Factor



**CIE Tristimulus values**

$$X_Q = 683 \int_{\lambda} L_Q(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y_Q = 683 \int_{\lambda} L_Q(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z_Q = 683 \int_{\lambda} L_Q(\lambda) \bar{z}(\lambda) d\lambda$$

**CIE 1931 chromaticity coordinates**

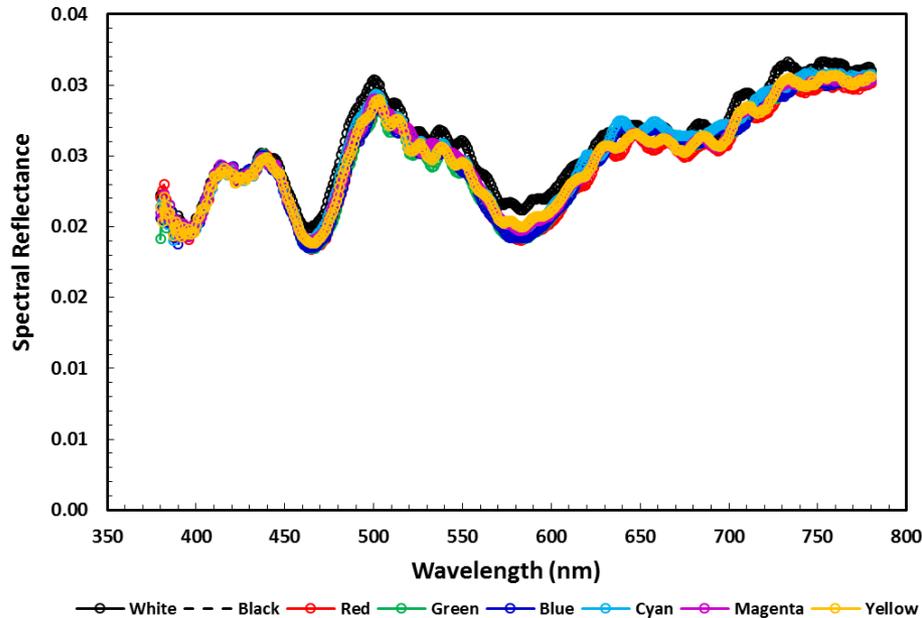
$$x_Q = \frac{X_Q}{X_Q + Y_Q + Z_Q}$$

$$y_Q = \frac{Y_Q}{X_Q + Y_Q + Z_Q}$$

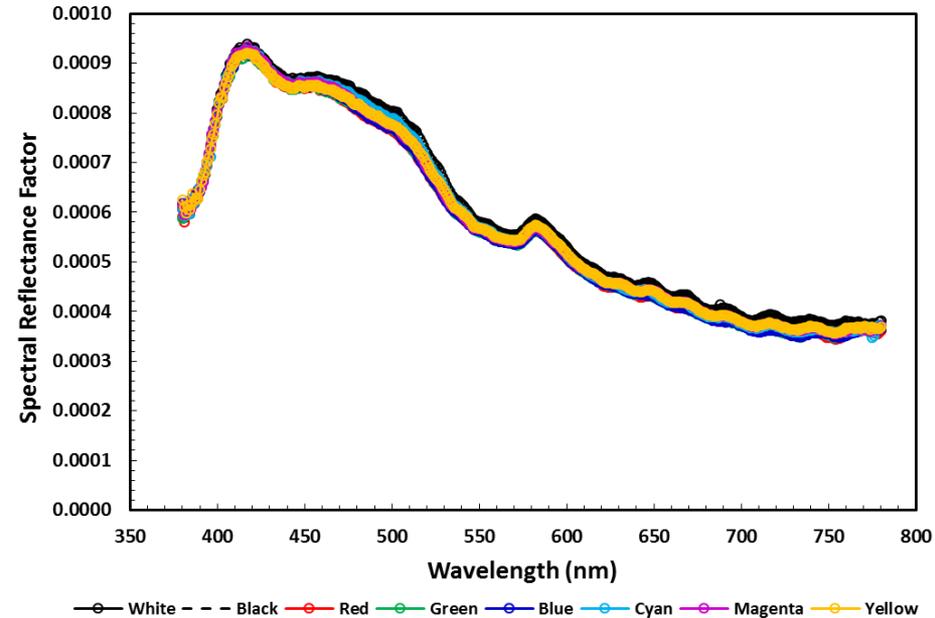
# Reflectance Factor Results

Reflection performance of the transparent LCD display.

## Hemispherical Spectral Reflectance



## Directional Spectral Reflectance Factor



Minimal rendered display color dependence.

# Photometric Results

Spectral to luminous transmittance factor:

$$T_{CIE-D} = \frac{\int T_{test}(\lambda) E_{CIE-D}(\lambda) V(\lambda) d\lambda}{\int_{\lambda} E_{CIE-D}(\lambda) V(\lambda) d\lambda}$$

$V(\lambda)$  = photopic luminous efficiency function

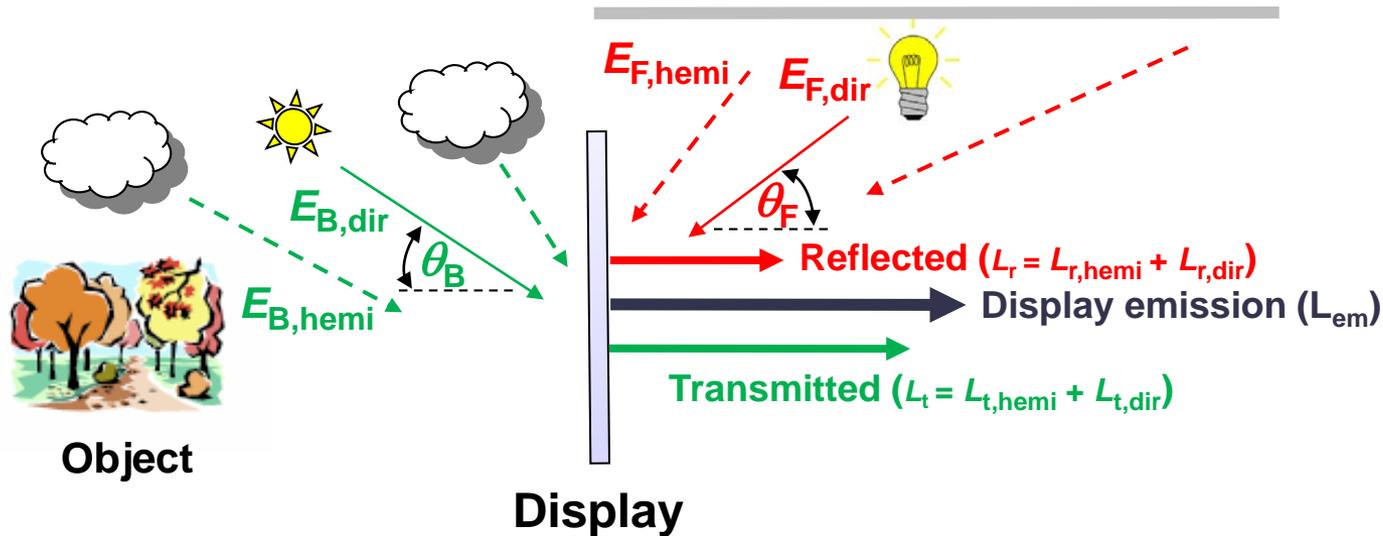
$E_{CIE-D}$  = ideal source spectrum (e.g. CIE D-Illuminant).

Transparent LCD luminous reflectance and transmittance factor results.

Light source	Front reflection coefficient	Back transmission coefficient
Hemispherical diffuse (di/0)	white: $\rho_{F,hemi} = 0.025$	white: $T_{B,hemi} = 0.13$
	black: $\rho_{F,hemi} = 0.023$	black: $T_{B,hemi} = 0.00018$
Directional (Ring light, 45/0)	white: $R_{F,dir} = 0.00061$	white: $T_{B,dir} = 0.00061$
	black: $R_{F,dir} = 0.00059$	black: $T_{B,dir} = 0.000078$

# Transparent Display Performance

Define illumination contributions on display:



Use general equation to estimate total luminance:

$$L_Q = L_{Q,em} + \frac{\rho_Q}{\pi} E_{r,hemi} + \frac{R_{Q,dir}}{\pi} E_{r,dir} \cos \theta_r + \frac{T_{Q,hemi}}{\pi} E_{t,hemi} + \frac{T_{Q,dir}}{\pi} E_{t,dir} \cos \theta_t$$

Q = display color

# Summary

- **Highlighted the need for including transmission and reflection measurements for transparent displays.**
- **Showed how the display ambient performance can be simulated by a general formalism using transmission and reflection coefficients.**
- **Introduced the concept of transmittance factor and showed how it can be applied for hemispherical diffuse and directional light sources.**
- **Demonstrated the implementation of these methods on a transparent LCD display.**
- **These methods provide valuable information in the development of transparent displays.**