

6.3.1 CALIBRATION

Calibration has historically been somewhat difficult in flowing films, since illumination with a monochromatic light source can indicate only relative thickness changes, not absolute values. One often resorts to first imaging some external cell of known thickness for calibration. However, we've found that certain types of light sources can be used in concert with numerical calculations to allow an accurate measurement of absolute film thickness to be made from the color of the reflected light.

A derivation of the reflected intensity I_r from a thin film is easily found [95]. To first order it varies with incident intensity I_i , reflectivity R , wavelength λ , index of refraction μ , angle of refraction θ , and thickness h , as

$$I_r = 4I_i R \sin^2 \left(\frac{2\pi}{\lambda} \mu h \cos \theta \right). \quad (6.8)$$

We will not be concerned here with the explicit form of R , as it depends only on the angle of the incident light and the index of refraction of the solution, and, thus, doesn't change the spectral characteristics of the reflection.

The spectrum is shown for a couple of film thicknesses in Fig. 6.10 (illumination is by uniformly white light, $I_i = 1$). However, it is not immediately obvious what a film of this thickness actually *looks* like. To ascertain this, it is necessary to first understand something about how the human visual system works. The retina, or back wall of the eye, is covered with two types of specialized neurons, rods and cones. The rods lie outside of the central region of vision and respond primarily to brightness. Their response is strongly peaked toward the blue end of the spectrum (the reason

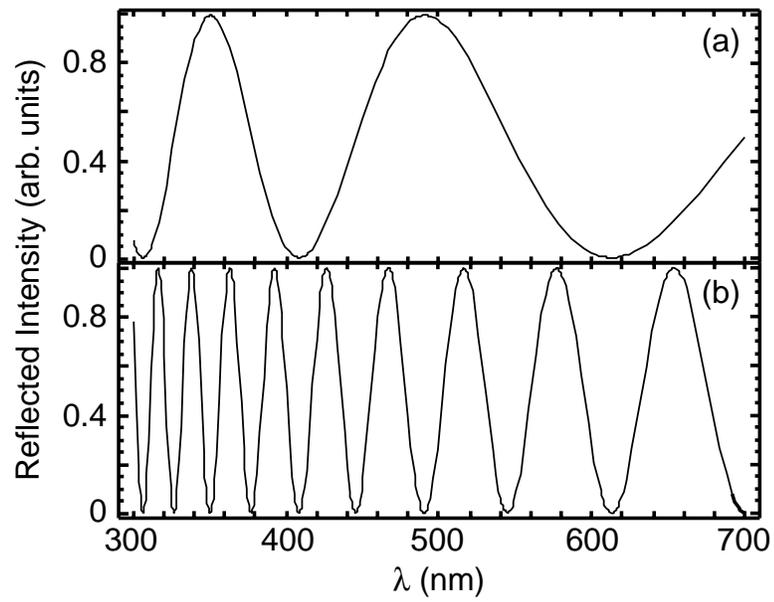


Figure 6.10: Spectrum of light reflected normal to a film of thickness (a) 500 nm, and (b) 2000 nm. Illumination is by uniform white light ($I_i = 1$).

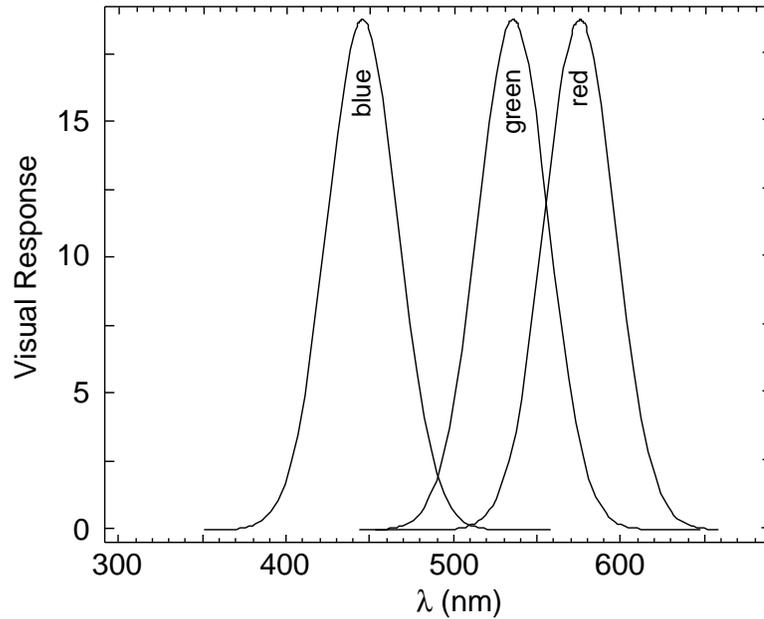


Figure 6.11: Modeled response of human visual system. Blue response is strongest near 445 nm, green near 535 nm, and red near 575 nm.

red light doesn't destroy night vision), and under optimal conditions can perceive individual photons of light [96].

The cones are responsible for color vision. They contain various forms of proteins called opsins which are sensitive only to certain regions of the spectrum. The principle sensitivity [97, 98] for blue opsin is at 445 nm, for green at 535 nm, and for red at 575 nm. The population of each type of cone varies dramatically (blue accounting for only 2%), though, the overall sensitivity of the visual system to each is nearly equal [96]. In the present paper we will assume that the spectral response of the cones is approximately Gaussian with width $\sigma = 30$ nm (narrower implies more saturated

colors, wider more washed out).

Our perception of color is, therefore, not a detailed map of the spectral characteristics of an object, but rather a weighted average which compresses this information into three variables,

$$C_j(t) = \int_{-\infty}^{\infty} K_j(\lambda) I_r(\lambda, t) d\lambda, \quad (6.9)$$

where,

$$K_j(\lambda) = \frac{1}{\sigma\sqrt{\pi}} \exp \left\{ - \left(\frac{\lambda - \lambda_j}{\sigma} \right)^2 \right\}, \quad (6.10)$$

and $j \in \{ \text{RED, GREEN, BLUE} \}$. The resulting color components $C_j(t)$ for a given thickness are then sufficient information to generate the perceived color using any number of utilities (in our case MATHEMATICA).

The reflected color is shown for films ranging in thickness from 10-2500 nm in Fig. 6.12 (a). Part (b) shows the effect of viewing the film at a glancing angle of 75 degrees to the normal. Notice that for films of thickness less than roughly 50 nm, there is almost a complete cancellation of the light across all wavelengths. Soap films in this thickness range are called common black films.

The difficulty is that for thicker films the oscillations in the reflected light intensity (as a function of λ) occur on a scale much shorter than the width of the response curve for the opsins (compare Figs. 6.10(b) and 6.11). The effect occurs first at shorter wavelengths. The result is that the blue contribution to the perceived color remains nearly constant, and thus for films thicker than roughly a half micron, the

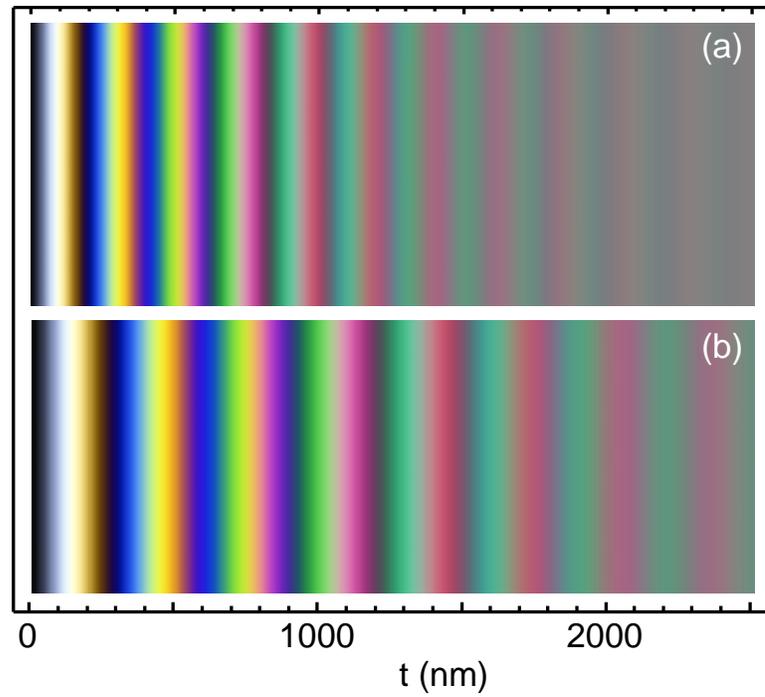


Figure 6.12: Variation in color of light reflected from thin film when viewed from (a) normal to the film, or (b) at a 75 degree angle to the normal.

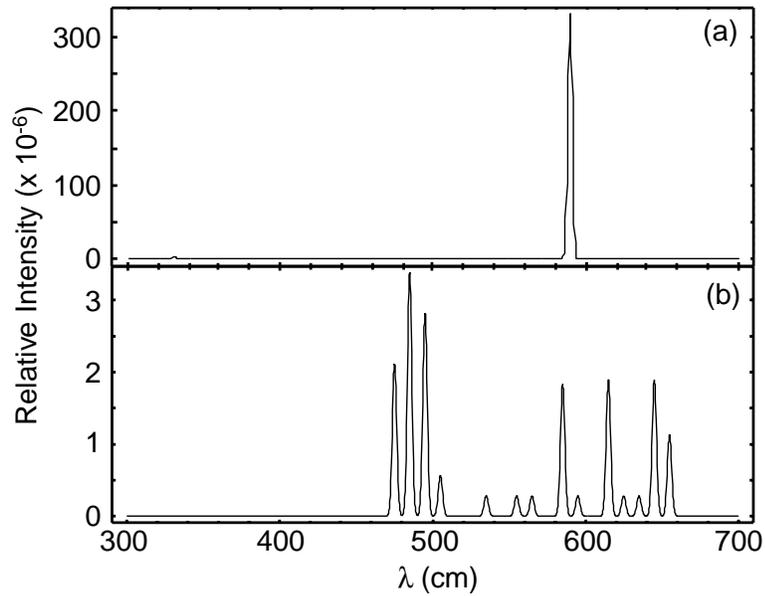


Figure 6.13: Spectral lines for (a) Na, and (b) Xe.

reflected color oscillates only between green and red. For films thicker than a couple of microns, even the longer wavelength portion of the spectrum begins to wash out noticeably, thus, severely limiting the usefulness of the method for obtaining accurate measurements of films thicker than a micron or so.

One solution rests in the use of light with non-uniform spectral characteristics. This can be accounted for by letting $I_i \rightarrow I_i(\lambda)$. Typically, the form of this factor is dictated by the characteristics of various plausible laboratory light sources. Atomic spectra data [99] can be used to create the emission profile for various lamps, singly, or in combination. The functional form of $I_i(\lambda)$ is modeled by a sum of narrow

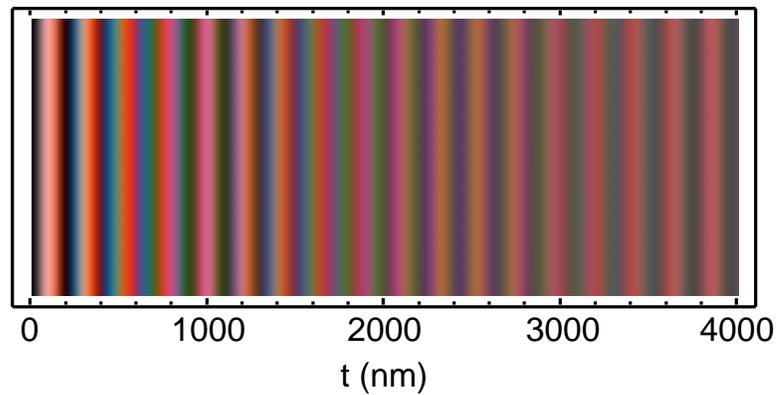


Figure 6.14: Variation of color reflected from thin film under illumination by a xenon lamp.

Gaussian distributions with centers determined by the location of the spectral lines, and amplitudes set by their relative strength.

Emission spectra for sodium and xenon lamps are shown in Fig. 6.13. The sodium lamp is monochromatic. The oscillation between almost completely destructive and completely constructive interference, thus, leads to stunning visual topographic maps of the film thickness. However, it provides no information about the absolute thickness, only relative changes.

Calculations were done with various other light sources as well, including: neon, helium, and krypton. Neon and helium suffer the same fate as sodium. Krypton vacillates between bands of red, blue, and purple. Only xenon appears a likely candidate for absolute thickness measurements. In addition to short wavelength oscillations between color pairs (in thickness-space), there is a longer wavelength change in the color

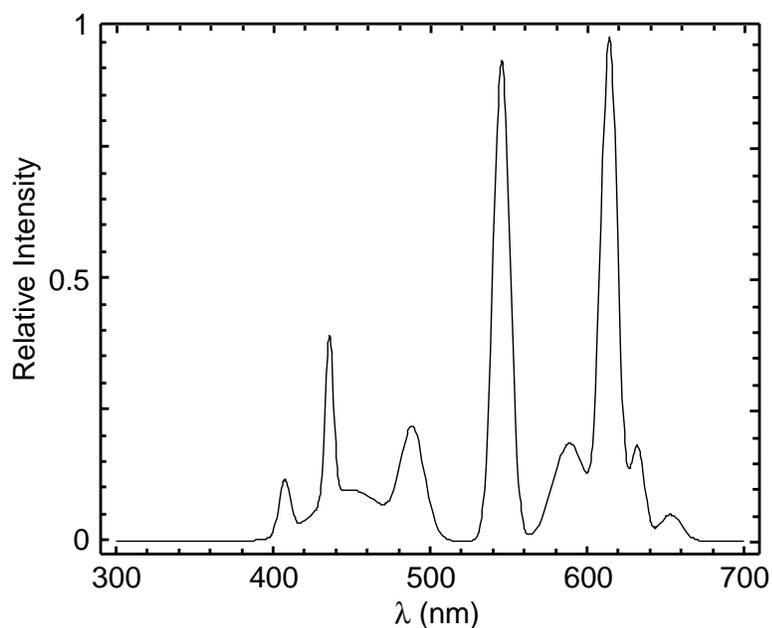


Figure 6.15: Spectral lines for Philips TL735 fluorescent lamps. Magnitude of peaks only shows relative intensities.

of the bands which can be used to make a determination of the absolute film thickness. One drawback to xenon, however, is a decrease in brightness when compared to sodium of roughly two orders of magnitude.

Fluorescent lamps are another possible source of film illumination. We noticed two interesting things about the film when viewed under ordinary laboratory lights (Philips TL735 fluorescent lamps): first, the oscillation between green and pink bands in the reflected light persisted to much greater film thicknesses than expected from Fig. 6.12 (b) (where the saturation of the colors appears to wash out after only

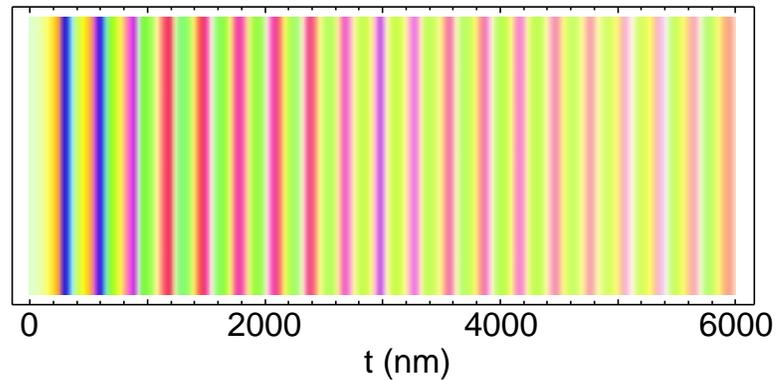


Figure 6.16: Variation of color reflected from thin film under illumination by Philips TL735 fluorescent lamps. Viewing angle is 75 degrees. Colors were individually scaled so that for each t the largest $C_j(t)$ was always 1. This simulates what one actually sees when looking at the reflection of an illuminated surface.

a few oscillations); and second, there were occasionally bands of purple among the pink-green pairs which were not accounted for by an assumption of uniformly white light.

The spectrum for the Philips TL735 lamp is shown in Fig. 6.15. It has three prominent peaks situated near the regions of peak sensitivity for the three opsins. This maximizes the effective brightness of the lamps for a given power output, and ensures that we perceive the lamps to be nearly white in color (the slightly higher magnitude of the red and green lines makes for a warmer light). However, since the contributions to the white light come from narrow peaks rather than from uniformly across the spectrum, the washing out that occurs with truly white light doesn't occur until much later.

The calculated colors reflected from the film under illumination from such a fluorescent lamp are shown in Fig. 6.16. As is experimentally observed, the color bands remain saturated to much greater thicknesses than is expected for illumination by uniform white light. Further, a prominent purple band is observed at a film thickness of $3\ \mu\text{m}$ (when the film is viewed at a 75° angle to the normal). This band therefore provides a recognizable marker at a thickness which is easily obtainable in vertically falling soap films. Calibration at other specific thicknesses can be accomplished by counting pink-green oscillations from this known marker.

6.3.2 FLUORESCENCE

The ability to compute the absolute film thickness from interference fringes allows for the calibration of other methods by which the thickness can more readily be determined experimentally. The addition of a small quantity of fluorescent dye to the solution, for example, allows for the determination of the film thickness from the fluorescent intensity of the film when illuminated by the PIV strobes. A series of calibration measurements, done at a number of different interference-fringe determined thicknesses, allows for the computation of the gradient (dI/dh) (where I is the measured fluorescent intensity, and h the film thickness). This calibration process, however, is complicated by two factors: first, a spatially uneven illumination of the film by the strobe lamps may indicate variations in the film thickness which don't really exist; and second, thicker films really do vary in thickness across their width,