# *Study Guide: Physical Optics*

1. **Describe a wave front. Figure 5.1 b & 5.2 a & b**
Wave (physical) optics treats light as a series of propagating electric and magnetic field oscillations. While we cannot see these extremely rapid oscillations, their wave behavior is similar to that of water waves. Thus, we find it useful to picture waves in terms of simple water waves, such as those created by a bobbing cork on an otherwise quiet pond. See Figure 5-1a. The bobbing cork generates a series of surface disturbances that travel radially outward from the cork. The surface disturbances are mostly up and down (*transverse* vibrations), propagating in a direction perpendicular to the vibrations. Figure 5-1b shows the same disturbances traveling away from point *A* (the cork) as a series of successive *wave fronts* labeled *crests* and *troughs*. A *wave front* is defined as a series of adjacent points along which all motions of the wave are identical. The solid circles in Figure 5-1b depict outward-moving wave fronts that are wave *crests*—maximum displacements up; the dashed circles represent outward moving wave fronts that are wave *troughs*—maximum displacements down. Adjacent crests are always a *wavelength* apart, as are adjacent troughs.

2. **Describe the relationship between light rays and wave fronts.**
In effect, then, we are saying that, with large objects such as prisms, mirrors, and lenses—large in the sense that their dimensions are millions of times that of the wavelength of light—interference and diffraction effects—as described briefly in Module 1-4, *Basic Geometrical Optics*—are still present in the imaging process. But, they occur on a scale so small as to be hardly observable to the naked eye. To a good approximation, then, with "large" objects we are able to describe light imaging quite satisfactorily with geometrical (ray) optics and obtain fairly accurate results. But, when light waves pass around small objects, such as a 100 μm diameter human hair, or through small openings, such as a 50 μm pinhole, geometrical or ray optics *cannot* account for the light patterns produced on a screen beyond these objects. Only wave optics leads to the correct interpretation of such patterns.

3. **Define phase angle and its relationship to a wave front.**
The phase angle is the *same for any point on a given wave front*. The displacement of a point (*Y)* is graphed against the phase angle α, expressed in radians. As the phase angle α increases, the displacement point (*Y)* changes in accordance with the *sine wave* $Y = A \sin \alpha$. One complete wave oscillation (360º or 2π radians) produces one wavelength, or one period, of the wave. Thus, any point along a wave can be specified by its *phase angle* α. The *phase* of any point on a wave is defined as "the angular displacement" of that point from the last positive zero crossing of the wave. A "positive zero crossing" occurs at those zero displacement points where the new displacement is about to become positive.

4. **State the principle of superposition. Figure 5.4 & 5.5**
"What happens at a certain point in space when two light waves pass through **that point** at the same time?" To answer this question, we make use of the *principle of superposition*, which says:
> *When two or more waves move simultaneously through a region of space, each wave proceeds independently as if the other were not present. The resulting wave "displacement" at any point and time is the vector sum of the "displacements" of the individual waves.*

This principle holds for water waves, mechanical waves on strings and on springs (the Slinky!), and for sound waves in gases, liquids and solids. Most important for us, it holds for all electromagnetic waves in free space.

5. **State Huygens' principle. Figure 5.6 a & b**
Long before people understood the electromagnetic character of light, Christian Huygens—a 17th-century scientist—came up with a technique for propagating waves from one position to another, determining, in effect, the shapes of the developing wave fronts.
> *Each point on a regularly-shaped or oddly-shaped wave front in a given medium can be treated as a point source of secondary, spherically-shaped wavelets. These secondary wavelets spread out in all directions with a wave speed characteristic of that medium. The developing wave front at any subsequent time is the envelope of these advancing secondary wavelets.*

6. **State the conditions required for producing interference patterns.**
An understanding of light wave interference begins with an answer to the question, "What happens at a certain point in space when two light waves pass through that point at the same time? Figure 5.5. Constructive and destructive. Huygen's principle: basic to a quantitative study of interference. Overlapping light waves from 2 sources each with a fixed wavelength and phase relationship creating a "coherence of sources" which is a stringent requirement. As these coherent sources overlap one another when they are in phase it creates constructive interference. When out of phase, destructive.

7. **Define constructive and destructive interference. Figure 5.7**
Constructive: resultant interference when overlapping coherent sources are in phase.
Will have maximum intensity; crest meeting crest, trough meeting trough
Destructive: resultant interference when overlapping coherent sources are out of phase.
Will have minimum intensity; crest meet trough.
Take a look at 1. and 2. below, which were noted in the margins of your textbook A 85, 87.
See this in the box in the middle of page 3, Mod 1.5:

The numbers below the A that appears in several marginal places in this module reference specific applets that demonstrate the concepts being described in the text. These applets are accessible at http://optecvideo.opteccrm.org/.

1. http://www.optecvideo.opteccrm.org/course1-ebook-widgets/Module3/Widget3-2/Module3_Widget2_Final2.html
2. http://www.optecvideo.opteccrm.org/course1-ebook-widgets/Module1/Widget1-4/Module1_Widget_4_Final.html

**8. Describe a laboratory setup designed to produce a double-slit interference pattern.**
**Figure 5.8** Shows the general laboratory setup for producing interference fringes with light from two coherent sources $S_1$ and $S_2$. Source $S_0$ is a monochromatic (single wavelength) point source of light whose spherical wave fronts (circular in the drawing) fall on the two slits to create secondary sources $S_1$ and $S_2$. Spherical waves radiate out from the two secondary sources $S_1$ and $S_2$ and maintain a fixed phase relationship with each other. As they spread out and overlap (interfere) at the screen, they produce a series of alternate bright and dark regions. The alternate regions of bright and dark are referred to as interference fringes. Figure 5-8b shows such interference fringes, greatly expanded, for a small central portion of the screen shown in Figure 5-8a.

(a) Light from slits *S*1 and *S*2 must be coherent; that is, there exists a fixed phase relationship between the waves from the two sources.
(b) Light from slits *S*1 and *S*2 must be of the same wavelength.

Use *A 13* in margin for better understanding and what happens with changes. Study Example 3.

**9. State the conditions for an automatic phase shift of 180° at an interface between two optical media.**
When thin films of different refractive indexes and thicknesses are appropriately stacked, coatings can be created that either enhance reflection greatly (HR or *high-reflecting* coats) or suppress reflection (AR or *anti-reflecting* coats). The geometry for thin-film interference is shown in Figure 5-10. We assume that the light strikes the film—of thickness *t* and refractive index *nf* —at near-normal (perpendicular) incidence. In addition, we take into account the following *established* facts:

- A light wave traveling from a medium of lower refractive index to a medium of higher refractive index *automatically undergoes a phase change of π (180°)* upon reflection. A light wave traveling from a medium of higher index to one of lower index *undergoes no phase change* upon reflection.
- The wavelength of light $\lambda n$ in a medium of refractive index $n$ is given by $\lambda n = \lambda 0/n$, where $\lambda 0$ is the wavelength in a vacuum or, approximately, in air.

**10. Describe how diffraction differs from interference. Figure 5.13**
The ability of light to bend around corners, a consequence of the wave nature of light, is fundamental to both interference and diffraction. Diffraction is simply any deviation from geometrical optics resulting from the obstruction of a wave front of light by some obstacle or some opening. Diffraction occurs when light waves pass through small openings, around obstacles, or past sharp edges. Diffraction considers the contribution from *every part of the wave front* passing through the slit. By contrast, when we looked at interference from Young's double slit, we considered *each slit* as a point source, ignoring details of the portions of the wave fronts in the slit openings themselves.

**11. Describe single-slit diffraction. Figure 5.14**
The overall geometry for diffraction by a single slit is shown in Figure 5-14. The slit opening, seen in cross section, is in fact a long, narrow slit, perpendicular to the page. The shaded "humps" shown along the screen give a rough idea of intensity variation in the pattern. The sketch of bright and dark regions to the right of the screen is intensified to simulate the actual fringe pattern seen on the screen—even though the "artistic recreation" does not show the actual drop-off of intensity indicated by the "intensity humps." We observe a wide central bright fringe, bordered by narrower regions of dark and bright. The angle θ shown connects a point P on the screen to the center of the slit.

**12. Distinguish between Fraunhofer (far-field) and Fresnel (near-field) diffraction.**
If **coherent** light falling on a diffraction aperture, such as a pinhole or a narrow slit, is **collimated**, and if the diffracted light is observed on a **distant** screen, the diffraction pattern formed there is described as Fraunhofer diffraction. In high energy lasers, **Fraunhofer diffraction is often referred to as far-field diffraction** or diffraction in the far-field. Such diffraction patterns were first investigated and explained mathematically by Joseph von Fraunhofer (1787–1826). Study Figure 5.16: the general setup for observing "far-field" or Fraunhofer diffraction patterns is shown. Read to understand Figure 5.16. Using a laser on the source side and a positive lens on the screen side allows one to form and study Fraunhofer diffraction patterns with ordinary lab tables. Study Equation 5.16.

When the conditions (or their equivalence) for "distant source" and "far-removed screen" are **not satisfied** diffraction patterns are still formed. These are referred to as **Fresnel diffraction, or near-field diffraction**, after Augustin Fresnel (1788–1829), who explained their more complicated details with much more complicated mathematics. Most basic books on optics cover both the Fraunhofer and Fresnel mathematical analyses of diffraction patterns.

**13. Identify typical Fraunhofer diffraction patterns for a single slit, circular aperture, and rectangular aperture.**
Study Figures 5.17, 5.18, 5.19 & 5.20 and their relative equations.

14. **Describe a transmission grating. Figure 5.20, A 79 & 80**
If we prepare an aperture with thousands of slits, separated by equal spacing, we have a so-called transmission-diffraction grating. The width of a single slit—the opening—is given by *b*, and the distance between slit centers is given by *a*. For clarity, only a few of the thousands of slits normally present in a grating are shown. Note that the spreading of light occurs always in a direction perpendicular to the direction of the long edge of the slit opening—that is, since the long edge of the slit opening is vertical in Figure 5-20, the spreading is in the horizontal direction—along the screen. For the remainder of this discussion, the terms lines, grooves, or slits are used interchangeably. The resulting diffraction pattern is a series of sharply defined, widely spaced fringes, as shown. The central fringe, on the symmetry axis, is called the zeroth-order fringe. The successive fringes on either side are called lst order, 2nd order, etc., respectively. They are numbered according to their positions relative to the central fringe, as denoted by the letter m, and are signed as positive or negative. The intensity pattern on the screen is a superposition of the diffraction effects from each slit as well as the interference effects of the light from all of the adjacent slits. The combined effect is to cause overall cancellation of light over most of the screen with marked enhancement at the bright regions, as shown in Figure 5-20.

15. **Describe what is meant by diffraction-limited optics.**
The size of a focal spot —structure and all— (per the previous discussion) is limited by diffraction. No matter what we do, we can never make the airy disk smaller than that given by $2R = 2.44\, f\lambda/D$. That is the limit set by diffraction. So, all optical systems are limited by diffraction and consequently limited in their ability to form true point images of point objects. We recognize this when we speak of diffraction-limited optics. An ideal optical system therefore can do no better than that permitted by diffraction theory. A real optical system will not achieve the quality limit permitted by diffraction theory. Real optical systems are therefore poorer than those limited by diffraction only. We often refer to real systems as many-times diffraction limited and sometimes attach a numerical figure such as “five-times diffraction-limited.” Such a reference indicates the deviation in quality expected from the given system compared with an ideal “diffraction-limited” system.

16. **Describe how polarizers/analyzers and the Law of Malus are used to control light intensity.**
When randomly polarized light (**Figure 5.25**) passes through a polarizer, the light intensity is reduced, since only the E-field component along the transmission axis (TA) of the polarizer is passed. When linearly polarized light is directed through an analyzer (another polarizer) and the direction of the E-field is incident at an angle $\theta$ to the transmission axis of the analyzer, the light intensity is likewise reduced. The reduction in intensity is expressed by the Law of Malus, given in Equation 5-26.

17. **Describe how Brewster windows are used in a laser cavity to produce a linearly polarized laser beam.**
Unpolarized light—the light we normally see around us—can be polarized through several methods. The polarizers and analyzers we have introduced, polarize by *selective absorption*. Another method of producing polarized light is by reflection. **Study Figure 5-27** as it shows the complete polarization of the reflected light at a particular angle of incidence B, called the Brewster angle. The reflected E-field coming off at Brewster’s angle is totally polarized in a direction in and out of the paper, perpendicular to the reflected ray (shown by the dots •). This happens only at Brewster’s angle, that particular angle of incidence for which the angle between the reflected and refracted rays, $B + \beta$, is exactly 90°.