LU05: Physics of Waves and Light Interference

Let's take a look at wavefronts and how they try to make it through and around optics and objects. A good understanding of how light propagates like a wave is a must for technicians. One type of light source is a point source. A true point source is like a spark from a spark plug. Light from this tiny source travels out in all directions. The combination of all of the photons from this source travel together as waves oscillating together. A similar mechanical example are water waves generated by a fishing bobber in a pond. As the source, the bobber, oscillates up and down, new wavefronts are generated, and travel out in concentric circles from the source. Light waves, even though they are so small we cannot see them propagating, still travel the same way; only the distance from one wave to the next is less than a micrometer. The wavefronts exist; for now, you'll have to take my word for it.

Electromagnetic waves travel out on their own. As they are oscillating, they reach different levels of displacement. The maximum upward displacement is called a crest. The maximum downward displacement is a trough. If we are moving along the optical surface of the waves, the distance from crest to crest or trough to trough is the wavelength. If we measure the time it takes to move from crest to crest, that will be the period. And, the number of times the wave repeats in one second is the frequency, which is a constant. Again, light is Electromagnetic. It has an electric field oscillating perpendicular to a magnetic field. A change in electric field causes a change in magnetic field, and vice versa. We will focus more on the electric field orientation and propagation in wave theory.

The principle of superposition is basically stating that when two waves meet their amplitudes will add. Sometimes this results in an increase in intensity, sometimes the result is NO light. It depends on the phase and position of each wave. Two incoherent waves passing the same place do not have a very noticeable resultant wave. They do interact, but the result is usually noise, or not significant enough to be usable. When coherent sources like lasers are used, results tend to be much more dramatic.

Now the question comes up, "How can I see the light from my laser pointer tip 90 degrees from the direction I point it?" In the 1600s a man by the name Christiaan Huygens attempted to prove this phenomenon. Christiaan Huygens was a busy man – designing microscopes, and looking at blood, reproductive cells, and germs. He even had spare time to use his telescope to look at the planets. His wave theory is one that explains a lot about how light moves. He broke the waves down into smaller segments, basically an infinite number of new point sources along each wavefront. The new point sources can spread in all directions. The tangent of each of the new point sources is the new main wavefront. Huygens' wavelets in each light source radiate waves in basically all directions. That includes off to the side 90 degrees. When two crests or troughs meet, the result is constructive interference and a bright area. When a trough meets a crest, don't expect there to be any light.

The more coherent the light source, the better the interference, brighter brights, and darker darks. Young's double slit experiment begins with a coherent light source and two tightly spaced very small slits. The slits need to be small enough, or their widths should be around the wavelength of light, or the width of a hair. The smaller the slit, the better the effects of diffraction and interference. Also, the spacing of the slits has a direct effect on the spacing of the interference pattern.

Another note to make is that the interference fringes continue out in the same pattern for 180 degrees. The bright fringe right in the middle is the zero fringe or the zero order fringe. As you progress outward from the center, the next fringe you come to is the 1st order fringe, then the 2nd order fringe, 3rd order fringe, and so on. If you travel in the opposite direction, the orders are -1st, -2nd, -3rd, and so on. Using results from Young's experiment, technicians can determine any of the many variables involved by taking a few precise measurements.

Let's look at a few:

- The spacing between the slits is 'a' or alpha
- The distance to the screen from the slits is 'd'
- The distance from the center or zero order fringe to the m^{th} order is 'y'
- The angle the order makes with the center of the slits is theta

$$y_B = \frac{\lambda d}{a} m \qquad \lambda = \frac{y_B a}{dm}$$

Young's work can be used for many applications. One would be to measure the wavelength of light from a coherent light source. You just must measure the distance to the screen, and the distance from the zero order to the m^{th} order. Re-arrange the formula and you have it.

Thin film interference is a phenomenon where reflections from two or more surfaces are out of phase with each other, and depending on the incident light, may cancel each other out or add together for a bright reflection. What happens is a portion of the light bounces off of the first surface and heads toward a detector. The rest of the light transmits through the film and reflects off of the next surface and back out of the thin film layer. The second reflection is out of phase with the first by the amount it traveled. In other words, their path lengths are different. If their path difference is equal to one whole wavelength or some whole number of wavelengths, then the two reflections generate a bright spot. If the path difference is an order of half wavelengths, the reflections cancel each other out. We can take the film thickness 't' and multiply it with the index of refraction 'n' of the film, multiply that by 2 because of two passes through the film, and we come up with '2nt' which is called the optical path length.

Most transmissive optics in laser or optical systems have AR coatings to reduce the degree of reflected light lost in the system. When light transitions from a low index to a higher index material, its phase is changed by 180 degrees. Reflections from straight glass tend to be on the order of 4% per surface. That is too much loss. So, thin films are deposited on the glass surface to reduce the reflections to practically zero.

The index of refraction of the coating is between the index of air and the index of the glass. The thickness of the coating is set up to allow for the reflections to be out of phase by 180 degrees and cancel each other out. When light transitions from a high to low index of refraction, there is no phase change. Coatings can be made where they are stacked; alternating high and low index of refraction. So, each reflection from all of the surfaces are in phase with each other enhancing the total reflection, making this a high quality mirror. Coatings can be stacked to perform many functions like AR and HR, also specialized filters to transmit or reflect certain wavelengths and block others. All because of wave interference.

LU05: Diffraction and Polarization

Diffraction is a natural optical phenomenon that occurs in all light beams of any wavelength. Diffraction occurs when light passes near or through an opaque edge or aperture. All optical systems will have an outer edge, usually an aperture that will be a physical element that truncates the beam. At the edge of the beam, light turns the corner because of diffraction. Huygens' wavelets send parts of beams interfering in the shadows. The shape of the aperture or slit will

determine the shape of the diffraction pattern. Up close to an aperture, as the beam begins to diverge due to diffraction, the beam shape is different than if it is allowed to reach further out. The beam interaction up close to the source is called near-field where the Fresnel Principle is in effect. Technicians must understand what the Fresnel beam characteristics are in the near-field as well as further out in the far-field.

The French scientist Fresnel spent much of his short life studying diffraction and received many awards for his work. If a laser beam is incident on a small width slit, smaller than the beam diameter, diffraction occurs at both edges of the slit. The diffraction pattern will spread most in the direction of the shortest slit dimension. Like squeezing a garden hose down, the water sprays out more in the smaller hose dimension. This is the same as Young's double slit experiment, except instead of two separate slits, one slit is used but the two edges still create a distinct diffraction pattern. The formula reads like this:

$$y_B = \frac{\lambda d}{a} m \qquad \lambda = \frac{y_B a}{dm}$$

From the formula above, the fringe distance 'y' is inversely proportional to the slit width 'b.' So, the smaller the slit, the wider the fringe spacing. If light passes through a long narrow slit, light spreads mostly in the direction that corresponds to the narrowest dimension of opening (up and down), and barely at all parallel to the slit (left and right).

German scientist Joseph von Fraunhofer was the first to explain mathematically "far-field" diffraction. Basically, far-field readings must take place "far" from the emitting aperture. Far-field patterns take on a whole new appearance because diffraction has had time to move portions of the beam to the edges. How do you know if you are in the far-field? As a general rule you should be 100 times the aperture area divided by the wavelength of light. So, the smaller the aperture, the closer you can be and still be in the far-field. Fraunhofer was a self-taught physicist who played a very important role in optical science. Fraunhofer is known as the founder of The German Optical industry.

If a beam analysis is performed closer than 'Z' it is said to be in the near field. Fraunhofer fringe patterns formed by a narrow slit will be pronounced perpendicular to the narrow dimension of the slit. The pattern will contain a wide, bright zero order fringe surrounded by successive dark and bright fringes that continue out 180 degrees. The half angle spread to the first dark fringe is found by dividing the wavelength of the incident light by the slit width (d). To find the half width of the central bright fringe, multiply the slit-to-screen distance by the wavelength then divide by the slit width. Or, multiply the half-angle divergence by the screen distance. All of this will work only if the screen is in the far-field.

For circular apertures, a target pattern is observed, called the airy pattern with a central airy disc. The airy disc is the zero order bright fringe, and the bright rings surrounding the airy disc are the 1st, 2nd, and so on order fringes. To insure you are in the Fraunhofer far-field the same rules apply to circular apertures as rectangular. Divide the area of the aperture by the wavelength of incident light. Pi times diameter squared divided by four is an area formula for circles.

For rectangular apertures, the shorter dimension will diffract more and have a wider fringe spacing. In this example you must be over 80 cm away from the aperture in order to be out of the near field and into the far-field. At 80 cm away from the aperture the radius of the central bright fringe is nearly 8 mm. This is just barely into the far-field.

Each time an extra slit is added to the situation, the interference pattern becomes more complex. For instance, with two slits, each of the bright fringes is broken up into many smaller fringes. The tighter the spacing between the slits, the wider the fringe spacing becomes. When a device is constructed where there are hundreds or thousands of slits in an

inch or mm, we call that a diffraction grating. Diffraction gratings are useful for many measurement techniques involving wavelength. Diffraction gratings of many types like transmission gratings or reflection gratings are used to measure wavelengths in spectrometers, monochromators, and spectrophotometers. The grating equation determines source wavelength by measuring the angle between the zero order and the first order. In the lab you will measure the distance from the grating to a screen and the distance from the zero order and the first order to determine wavelength. Use trigonometry to solve for the angle and substitute into the grating equation.

If white light or multiwavelength sources are incident on a diffraction grating, the light is split into the various orders. The zero order will be white; each of the other orders will be dispersed into their component frequencies. In other words, each of the higher orders will contain all of the wavelengths separated within the order. If a point source or an object a long distance from a lens is focused or imaged onto a screen near the focal point of the lens, with our eye we see a tiny bright spot. However, because of diffraction, there is a small airy pattern on the screen. Or, the image is not perfectly crisp. Even with the best “diffraction limited” optics there still is an airy pattern. With a long focal length lens, technicians can simulate the far-field images within the lab using bench working distances.

Remember, light is electromagnetic and we measure polarization orientation with the oscillation orientation of the electric or E vector. When linear polarizers are placed in a non-polarized beam, selective absorption allows only one axis of polarization to transmit. If another polarizer is placed in the beam path with its orientation 90 degrees to the first polarizer, no light will exit. If the second polarizer, or analyzer is rotated some angle other than 90 degrees, some light will be transmitted. The amount of light transmitted is proportional to the square of the cosine of the angle difference between the two polarizers. This is the law of Malus.

Ideally, the closer the angle difference gets to 90 degrees, the less the transmission. For instance, at 89 degrees only 0.03% of the incident light will be transmitted. At 90 degrees 0% will be transmitted, because the cosine of 90 degrees is 0. This is not the case because no polarizer or polarized beam is perfect. There will always be some losses in polarization.

Brewster’s angle is just a clever way to polarize light by reflection. At a single angle of incidence (Brewster’s angle) no parallel polarized light is reflected off of a glass or other reflective surface. The “parallel” term means parallel to the plane of incidence which contains the incident ray, reflected ray, and surface normal.

Let’s use the rolling log theory that came from Benjamin Armentrout, an optical engineer from the University of Houston. He said if you are following a logging truck with the logs just tossed in the back in all orientations and the tailgate opened, which logs would be more likely to roll or bounce off of your windshield or hood? The logs lying along the glass surface would roll off. The logs that are pointing into your hood or windshield stand a good chance of going through.

A piece of glass in air that has an index of refraction (n) of 1.692 ends up with a Brewster’s angle of nearly 60 degrees. So light coming in at 60 degrees will not reflect any parallel polarized light. Only the perpendicularly polarized light will reflect off. If you wear polarized sunglasses, you can see this effect daily. Glare from car windshields disappears like magic. Some laser tubes are fitted with a couple of Brewster’s windows. These are intracavity reflective optics that will eventually weed out all of the perpendicular polarized light before it can be fed back into the laser by the feedback mirrors.