NATURE OF LIGHT & DIFFRACTION

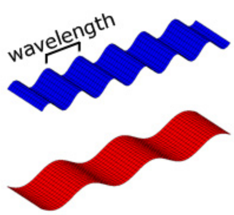
(Prepared by Prof. Hatice Altug)

In this course, we will make a tool called "spectrometer" to analyze light sources around us, such as white light and LEDs with different colors. The most crucial component of the spectrometer is a "diffraction grating". Grating has periodic groves on it and diffracts (bends) different colors to different angles.

Photonics

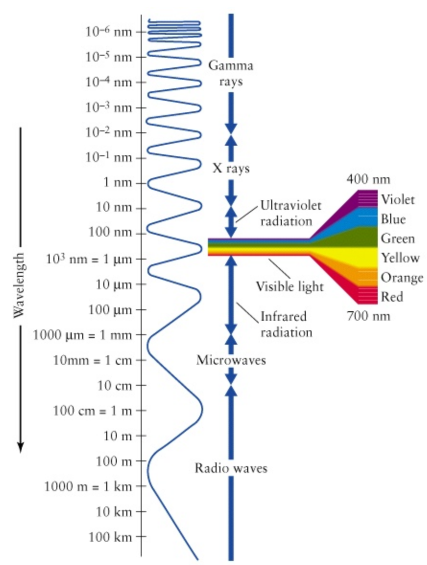
According to the *wave theory*, light propagates in space and time in terms of waves. The propagation of light is similar to the water wave propagation when you drop a stone in a water pond:

One of the most important parameter of waves (this could be light, sound, water or earthquake wave) is its wavelength. It is the distance between the repetitive patterns of wave:



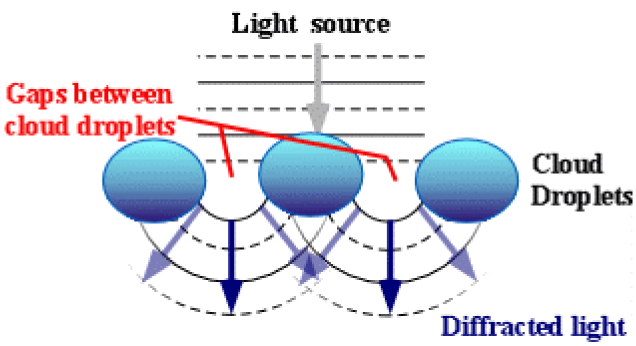
Our eyes are sensitive to light which lies in a very small region of the electromagnetic spectrum labeled "visible light". This "visible light" corresponds to a wavelength range of 400 - 700 nanometers (nm) and a color range of violet through red.

The human eye is not capable of "seeing" radiation with wavelengths outside the visible spectrum. The visible colors from shortest to longest wavelength are: violet, blue, green, yellow, orange, and red. Ultraviolet radiation has a shorter wavelength than the visible violet light. Infrared radiation has a longer wavelength than visible red light. The white light is a mixture of the colors of the visible spectrum. Black is a total absence of light. (Earth's most important energy source is the Sun. Sunlight consists of the entire electromagnetic spectrum, but our eye can only see the visible spectrum)



The visible light has nanometer scale and it is at the heart of nanotechnology. One subset of nanotechnology called *nano-photonics.* It deals with optical properties of nanostructures when the size is on the order of several tens of nanometer and thus comparable to the wavelength of light. (Another subset is *nano-electronics,* where scientists investigate the electrical properties of nanostructures).

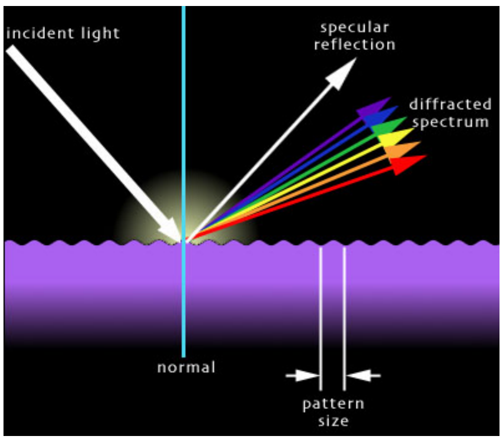
When light encounters an object, it bends differently depending on the size of object relative to its wavelengths. This type of light-object interaction in optics called **diffraction.** The effects is observed with all waves, including sound waves, water waves, and electromagnetic waves such as visible light, x-rays and radio waves. While diffraction occurs whenever propagating waves encounter an object, its effects are generally most pronounced for waves where the wavelength is on the order of the size of the diffracting objects. The complex patterns resulting from the intensity of a diffracted wave are a result of the superposition, or interference of different parts of a wave that traveled to the observer by different paths.



The effects of diffraction can be readily seen in everyday life and results in colorful examples. In the atmosphere, diffracted light is actually bent around atmospheric particles -- most commonly, the atmospheric particles are tiny water droplets found in clouds. Diffracted light can produce fringes of light, dark or colored bands. An optical effect that results from the diffraction of light is the silver lining sometimes found around the edges of clouds or coronas surrounding the sun or moon. The color of blue sky and romantic color of sunset could be explained by diffraction

Similarly, colors seen in spider web, CD, butterfly wings and soap bubbles are also partly due to diffraction (in addition to diffraction, they also involve another optical phenomenon called ***interference***)

This principle can be extended to engineer devices and components. One of the commonly used components based on diffraction is a ***diffraction grating***. It is an optical component with a regular pattern, which bends (diffracts) light into several beams travelling in different directions.



The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as a ***dispersive element***. Because of this, gratings are commonly used in monochromators and spectrometers.

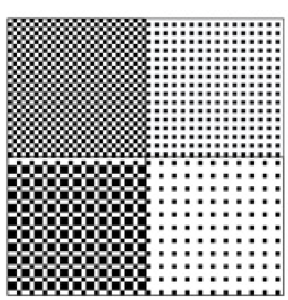
A photographic slide with a fine pattern of black lines forms a simple grating. For practical applications, gratings generally have grooves or rulings on their surface rather than dark lines. Such gratings can be either transparent or reflective. Gratings which modulate the phase rather than the amplitude of the incident light are also produced, frequently using holography.

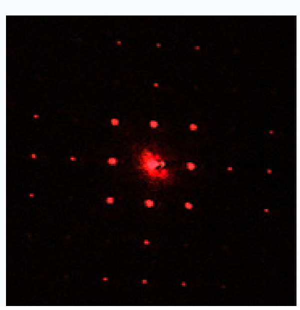
***I- In our experiment we will use transparent gratings & create beautiful patterns as follows*:**

Diffraction Gratings (four different kinds)

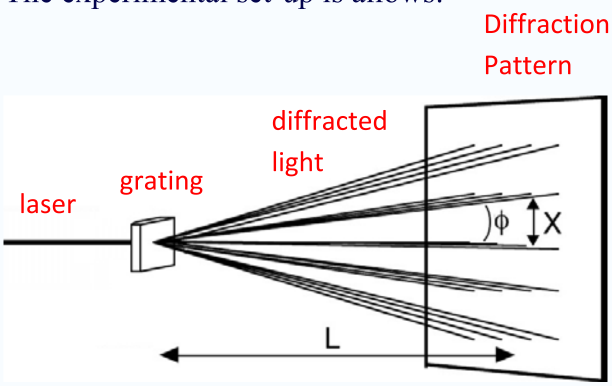
Diffraction Pattern With red light

Diffraction Pattern With White light





The experimental set-up is allows:



We will incident light on a diffraction grating with a fixed wavelength laser (red at 632.8 nm) and observe diffraction pattern on a screen

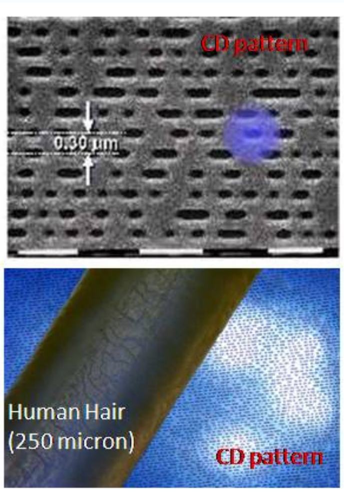
Fraunhofer theory relates diffraction angle (ϕ) to the wavelength of laser light (λ) with the grating periodicity (*d*) through the following equation:

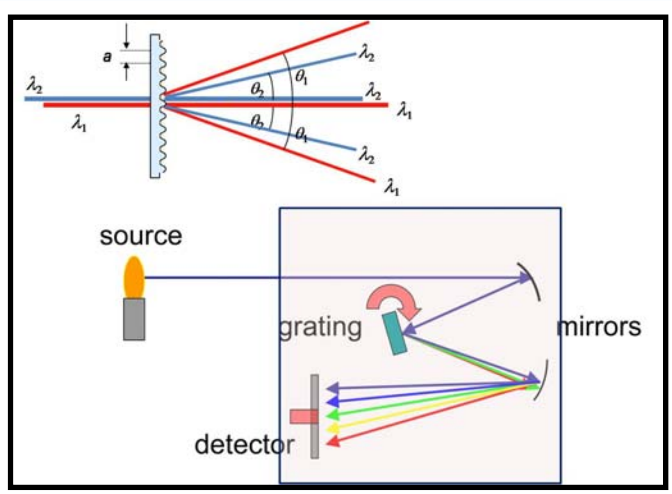
$d \sin(\phi) = \lambda.$

For small angles $\sin(\phi) \approx X / L$, where *X* is the diffraction spot spacing and *L* is the PDMS slab-to-screen distance. If we measure the angle ϕ and know the incident wavelength λ, then we can calculate the grating periodicity *d*.

II- In our experiment we will also make a <u>CD SPECTROMETER:</u>

In this spectrometer, CD/DVD acts as a grating element. If you take a high resolution image of an CD/DVD, you see that it is formed by fine grooves with sizes comparable to the wavelength of light. That is why when light interacts with CD, it gets diffracted. The diffraction angle depends on wavelength, so different colors will be spatially separated, enabling us to analyze the spectral content of different light sources.

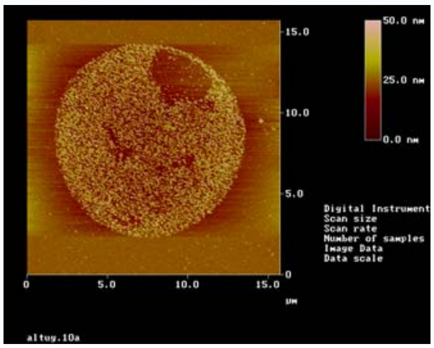




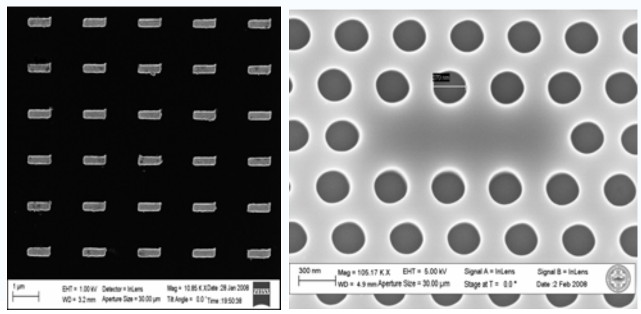
FURTHER READING

1) In our research (Dr. Altug's team), we also make diffractive structures but with more sophisticated patterns using nanofabrication. These structures are called ***photonic and plasmonic crystals***. We make new devices out of them such as **ultra-fast lasers** that can speed up our communication lines and **ultra-sensitive bio-sensors** that can enable detection of very low number of viruses and pathogens for early disease detection:

Captured viruses on a device surface. Imaged with Atomic Force Microscope. Note that the height of virus is 50 nanometer!! Virus is a nano-object.



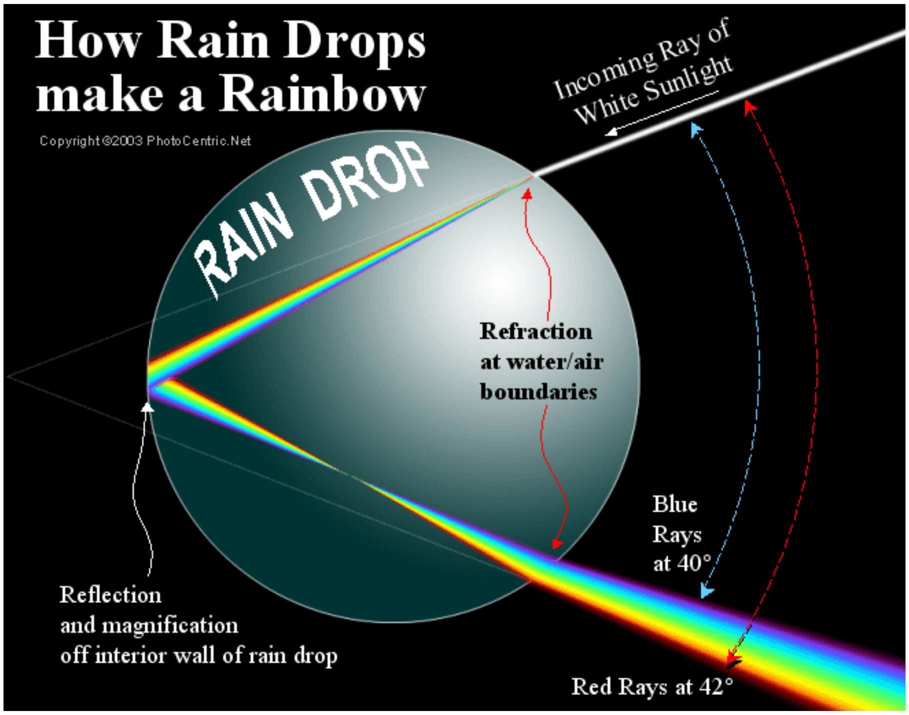
Fabricated Photonic and Plasmonic Crystal Structures. Imaged with Scanning Electron Microscope. For the left structure, the scale bar on the bottom shows 1 micron (1000 nanometer) while for the right, the scale bar is 300 nanometer.



2) Further reading: White light is made up of many different wavelengths which correspond to many different colors. When you shine white light onto an object, a rainbow sometimes forms due to how the light waves behave when they come in contact with an object. In this lab you saw one of these interactions, the diffraction grating, create rainbows on CDs and DVDs. Read on to learn how the rainbows that we see in the sky are formed because of another way in which light interacts with objects.

> The light is first refracted as it enters the surface of the raindrop, reflected off the back of the drop, and again refracted as it leaves the drop. The overall effect is that the incoming light is reflected back over a wide range of angles, with the most intense light at an angle of 40°–42°. The angle is independent of the size of the drop, but does depend on its refractive index. Seawater has a higher refractive index than rain water, so the radius of a 'rainbow' in sea spray is smaller than a true rainbow. This is visible to the naked eye by a misalignment of these bows. The amount by which light is refracted depends upon its wavelength, and hence its color. Blue light (shorter wavelength) is refracted at a greater angle than red light, but due to the reflection of light rays from the back of the droplet, the blue light emerges from the droplet at a smaller angle to the original incident white light ray than the red light. You may then think it is strange that the pattern of colors in a rainbow has red on the outside of the arc and blue on the inside. However, when we examine this issue more closely, we realize that if the red light from one droplet is seen by an observer, then the blue light from that droplet will not be seen because it must be

on a different path from the red light: a path which is not incident with the observer's eyes. The blue light seen in this rainbow will therefore come from a different droplet, which must be below that whose red light can be observed.



Contrary to popular belief, the light at the back of the raindrop does not undergo total internal reflection, and some light does emerge from the back. However, light coming out the back of the raindrop does not create a rainbow between the observer and the sun because spectra emitted from the back of the raindrop do not have a maximum of intensity, as the other visible rainbows do, and thus the colors blend together rather than forming a rainbow.

A rainbow does not actually exist at a particular location in the sky. Its apparent position depends on the observer's location and the position of the sun. All raindrops refract and reflect the sunlight in the same way, but only the light from some raindrops reaches the observer's eye. This light is what constitutes the rainbow for that observer. The position of a rainbow in the sky is always in the opposite direction of the Sun with respect to the observer, and the interior is always slightly brighter than the exterior. The bow is centered on the shadow of the observer's head, or more exactly at the antisolar point (which is below the horizon during the daytime), appearing at an angle of 40°–42° to the line between the observer's head and its shadow. As a result, if the Sun is higher than 42°, then the rainbow is below the horizon and cannot be seen as there are not usually sufficient raindrops between the horizon (that is: eye height) and the ground, to contribute. Exceptions occur when the observer is high above the ground, for example in an airplane, on top of a mountain, or above a waterfall.