Indian Institute of Technology, Kanpur
Department of Physics

PHY-224A: OPTICS
Lecture -1: Introduction to Optics

Date: 27 Jul 2016, Time :1700 hours Instructor: S.A. Ramakrishna

Dear Students,

Welcome to this course on Optics, which concerns the study of light. We perceive the world through our sense organs, and perception through sight is the predominating one over other senses like smell in human beings. Much of the human cerebral cortex is involved in vision. Thus, understanding light and its properties is very important to us in a personal sense. Further, Optics is an enabling technology, in the sense that advances in Optical technologies causes large and rapid advances in many other fields and technologies. Thus, the study of Optics is extremely important to a Applied Scientist, an Engineer and a Technologist. Carefully working through this course should equip you with a working knowledge of many optical concepts and techniques that you should be able to implement in many other areas of Physics and engineering.

This course on Optics will principally discuss the wave properties of light. Eventually, to be consistent and to address fully all its properties, light also has to be described quantum mechanically. But in order to reach that logical point, it is necessary to first understand the wave properties of light. In other words, we will only treat light as a classical electromagnetic wave here. Obviously then, the study of light will begin with a review of the Maxwell equations on which the whole edifice of electromagnetism is built upon.

Before doing that, I would like to discuss with you some phenomena in Optics where the wave nature of light is quintessential to understanding, where a theory like the corpuscular theory of Newton will simply not suffice.

Case 1: Lasers

You will all have seen or used a laser in some context or the other. So common is it nowadays. Yet there was a time when it was dubbed as a "solution seeking a problem", when the first lasers were developed. You would have seen a bright, highly collimated (directional), and monochromatic (single colored) beam emerging from a laser. Why is the laser spot so intense, so highly collimated, and appear like a single color? If you shine the laser on a painted wall or a piece of paper, you would have seen very bright tiny spots (called speckles) dancing around within the laser beam area and around it sometimes. These speckle spots seem to vary depending on the place on which the beam is incident, the direction from which you view them and so on. The question is why is the output of a laser occur with these properties while most other sources emit light that is so different?

The secret to all of this is that a laser beam principally consists of only a single (or a few) colors. In the language of waves, we call that a single color corresponds to a single wavelength of light. The laser essentially consists of a pair of highly reflecting mirrors and the distance between these mirrors is the determining factor as to which wavelengths can survive in the space between the mirrors (called the cavity), and hence be amplified and contribute to the laser output. It is a constructive interference of the waves within the cavity that allows waves with particular wavelengths to survive within the cavity. All other waves cancel themselves out due to what is called destructive interference. Each laser line has a bandwidth of wavelengths that is extremely small and determined by the reflectivity of the mirrors. The bandwidth of a laser can be much smaller than the bandwidth of light being emitted by atoms within the laser cavity. But all of this can be understood only if you think of light as waves.

Case 2: Optical pulses and pulse reshaping

You must have heard that very powerful lasers can emit pulses of light that can have powers as high as a few gigawatts or terawatts. But this large level of light output lasts for a very short time only, about 10^{-14} seconds or so. How are these massive amounts of powers packed into such short times? It turns out if one has a large number of waves with different frequcnies (or wavelengths), but with a fixed phase difference between them, they will constructively add up their fields only at certain instants of time. The larger the number of waves spanning larger bandwidths, smaller is the time interval over which they constructively add up and larger is the wave amplitude at that time. This is the secret to producing such ultra-short pulses with ultra-large intensities. Thus, the wave nature of light is critical to be able to create one of the most extreme objects ever developed by man.

Case 3: Photonic Bandgaps

You would have heard about the band theory of electrons in solids and the classification of solids into metals, insulators and semiconductors opn the basis of this theory. Here, the periodic potential of the lattice causes the electrons to be able to propagate in the crystalline solid only if they lie in certain energy ranges called bands. These bands are separated by bandgaps and that causes the principal properties of a solid.

Analogously, if one had a periodic arrangement of matter (refractive index variation), one can create bands and bandgaps for light propagating in that periodic medium. Light would be able to propagate through such a periodic medium, if and only if it had a frequency (or wavelength) that lies in a allowed band. Otherwise, light would not be able to propagate such a medium. This simply is again a consequence of constructure or destructive interference of waves that have scattered in this medium from the periodic scatterers. In the case of frequencies within a bandgap, the wave simply keeps returning due to destructive interference for propagation in any direction.

A photonic bandgap medium gives us a benchmark for darkness. It is absolutely dark at frequencies within the photonic bandgap inside the photonic crystal. Usually, one can dispell darkness by casting light, for example, by switching on the lamp in a dark room. But within the photonic crystal, a source will not be able to emit light at frequencies in the bandgap. For example, the probability for an atom to emit light gets severely impaired and the atom will not emit the energy as light and may prefer to decay to lower levels through non-radiative mechanisms. Such is the power of the darkness in a photonic bandgap medium.

Case 4: Polarization of light

Light has a property in addition to the other properties like color (wavelength), intensity etc. This property called polarization causes materials to respond differently to light of the same wavelength, intensity depending on the state of polarization. This polarization is realized as the plane in which the electric field of the electromagnetic wave is oscillating. Thus, it is a property that establishes light as a vector wave in contrast to a scalar wave such as a pressure wave. The polarization of light can be realized only if one attempts to describe light through the Maxwell equations. Polarization of light is changed in general, when light reflects off surfaces or when light scatters off small particles. There are many materials whose effects on light will not be polarization dependent. But there are a large class of materials which is alter ther state of polarization of light when it propagates through them. We will describe some such phenomena and materials whre the polarization of the light plays a determining role in this course later.

In each of the above cases, I invite all of you to read more about them; from books, from educational magazines like Resonance, from internet resources like wikipedia and so on. In all the above, you can see what differentiates a description of light as a wave and light as a particle stream is the ability to interfere constructively or destructively. This interference stems from the m ost basic assumptions of electromagnetic theory, namely, the linear superposition of electric and magnetic fields, whereby we add the fields vectorially. Thus, it is the fields that add on and not the intensities as particle beams would.