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The Propagation of Light

This chapter is about scattering, in particular, the absorption and prompt re-emission of electromagnetic radiation (EM) by electrons associated with atoms and molecules. The processes of transmission, reflection, and refraction are macroscopic manifestations of scattering occurring on a submicroscopic level. To begin the analysis, let’s first consider the propagation of radiant energy through various homogeneous media

1.1Rayleigh Scattering

Imagine a narrow beam of sunlight having a broad range of frequencies advancing through empty space. As it progresses, the beam spreads out very slightly, but all the energy continues forward and there is no scattering. Now, suppose we mix a wisp of air into the void—some molecules of nitrogen, oxygen, and so forth. These molecules have no resonances in the visible, no one of them can be raised into an excited state by absorbing a quantum of light, and the gas is therefore transparent. Instead, each molecule behaves as a little oscillator whose electron cloud can be driven into a ground-state vibration by an incoming photon. Immediately upon being set vibrating, the molecule initiates the re-emission of light. A photon is absorbed, and without delay another photon of the same frequency (and wavelength) is emitted; the light is elastically scattered. The molecules are randomly oriented, and photons scatter out every which way (Fig. 1.1).

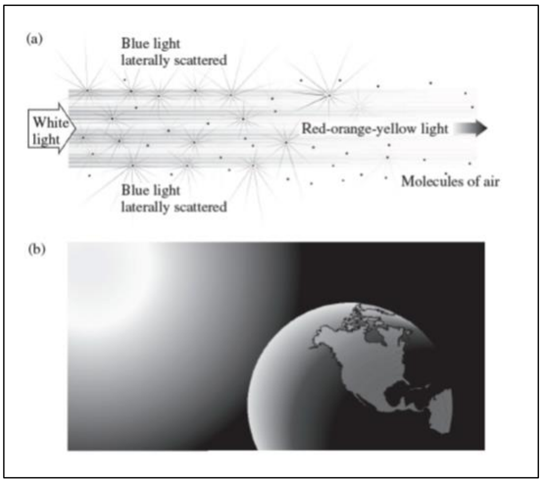

Figure 1. 1(a) Sunlight traversing a region of widely spaced air molecules. The light laterally scattered is mostly blue, and that’s why the sky is blue. The unscattered light, which is rich in red, is viewed only when the Sun is low in the sky at sunrise and sunset. (b) Solar rays reach about 18° beyond the daytime terminator because of atmospheric scattering. Over this twilight band the skylight fades to the complete darkness of night.

The amplitudes of these ground-state vibrations, and therefore the amplitudes of the scattered light, increase with frequency because all the molecules have electronic resonances in the UV. The closer the driving frequency is to a resonance, the more vigorously the oscillator responds. So, violet light is strongly scattered laterally out of the beam, as is blue to a slightly lesser degree, as is green to a considerably lesser degree, as is yellow to a still lesser degree, and so on. The beam that traverses the gas will thus be strong in the red end of the spectrum, while the light scattered out (sunlight not having very much violet in it, in comparison to blue, in the first place) will abound in blue. The human eye also tends to average the broad cacophony of scattered frequencies—rich in violet, blue, and green—into a background of white plus a vivid 476-nm blue, resulting in our familiar pale-blue sky.

Lord Rayleigh (1871) analysed scattered sunlight in terms of molecular oscillators. Using a simple argument based on dimensional analysis, he correctly concluded that the intensity of the scattered light was proportional to $\boldsymbol{1/\lambda^4}$and therefore increases with $\boldsymbol{v^4}$.

Before this work, it was widely believed that the sky was blue because of scattering from minute dust particles. Since that time, scattering involving particles smaller than a wavelength (i.e., less than about **λ/10**) has been referred to as **Rayleigh Scattering**. Atoms and ordinary molecules fit the bill since they are a few tenths of a nanometre in diameter, whereas light has a wavelength of around 500 nm. Additionally, non-uniformities, as long as they are small, will scatter light. Tiny fibres, bubbles, particles, and droplets all scatter.

Rayleigh Scattering the precise shape of the scatterers. The amount of scattering is proportional to the diameter of the scatterer divided by the wavelength of the incident radiation. Accordingly, the blue end of the spectrum is scattered most. A human's blue eyes, a bluejay's feathers, the blue-tailed skink's blue tail, and the baboon's blue buttocks are all coloured via Rayleigh Scattering.

1.1.1 Scattering and Interference

In dense media, a tremendous number of close-together atoms or molecules contribute a tremendous number of scattered electromagnetic wavelets. These wavelets overlap and interfere in a way that does not occur in a tenuous medium. As a rule, ***the denser the substance through which light advances, the less the lateral scattering,*** and to understand why that's so, we must examine the interference taking place.

The theory of Rayleigh Scattering has independent molecules randomly arrayed in space so that the phases of the secondary wavelets scattered off to the side have no particular relationship to one another and there is no sustained pattern of interference. That situation occurs when the separation between the molecular scatterers is roughly a wavelength or more, as it is in a tenuous gas. In Fig. 1.2a, a parallel beam of light is incident from the left. This so-called primary light field (in this instance composed of plane waves) illuminates a group of widely spaced molecules. In other words, the phases of the wavelets at P differ greatly. At any moment some wavelets interfere constructively, some destructively, and the shifting random hodgepodge of overlapping wavelets effectively averages away the interference. Random, widely spaced scatterers driven by an incident primary wave emit wavelets that are essentially independent of one another in all directions except forward. Laterally scattered light, unimpeded by interference, streams out of the beam.

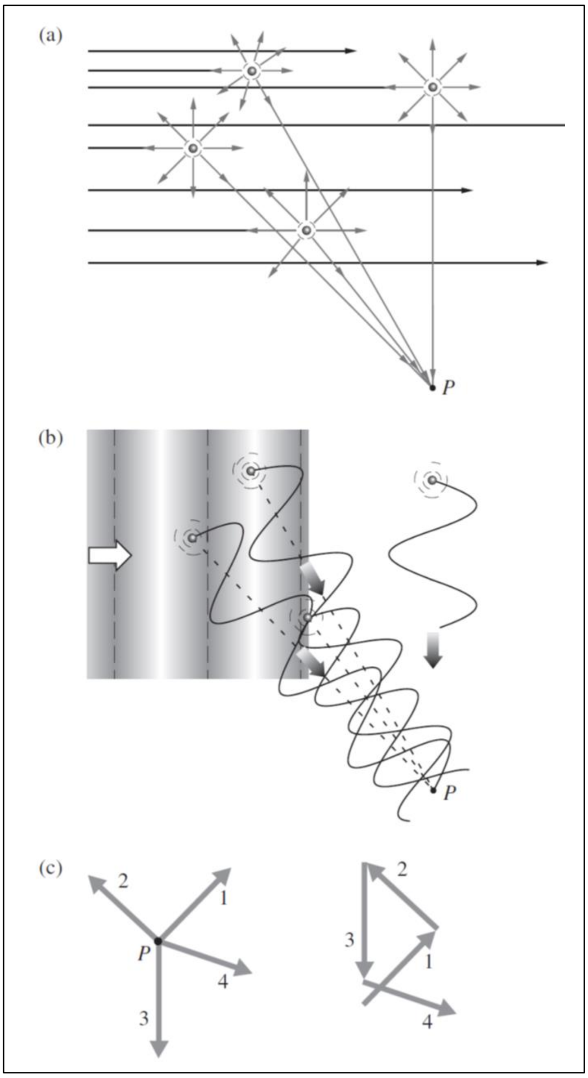

Figure 1. 2. Consider a plane wave entering from the left. (a) The scattering of light from a widely spaced distribution of molecules. (b) The wavelets arriving at a lateral point P have a jumble of different phases and tend not to interfere in a sustained constructive fashion. (c) That can probably be appreciated most easily using phasors. As they arrive at P the phasors have large phase-angle differences with respect to each other. When added tip-to-tail they therefore tend to spiral around keeping the resultant phasor quite small. Remember that we are really dealing with millions of tiny phasors rather than four substantial ones.

1.2.2 The Transmission of Light Through Dense Media

Now, suppose the amount of air in the region under consideration is increased. In fact, imagine that each little cube of air contains a great many molecules, whereupon it is said to have an appreciable optical density. The scattered wavelets ($\lambda \approx 500$ nm) radiated by sources so close together (≈ 3 nm) cannot properly be assumed to arrive at some point P with random phases—interference will be important. This is equally true in liquids and solids where the atoms are 10 times closer and arrayed in a far more orderly fashion. Again, the scattered wavelets interfere constructively in the forward direction, but now destructive interference predominates in all other directions. ***Little or no light ends up scattered laterally or backwards in a dense homogeneous medium.***

To illustrate the phenomenon, Fig. 1.3 shows a beam moving through an ordered array of close-together scatterers. Thus, some molecule A radiates spherically out of the beam, but because of the ordered close arrangement, there will be a molecule B, a distance $\approx \lambda/2$ away, such that both wavelets cancel in the transverse direction. Here, where λ is thousands of times larger than the scatterers and their spacing, there will likely always be pairs of molecules that tend to negate each other's wavelets in any given lateral direction. The more dense, uniform, and ordered the medium is (the more nearly homogeneous), the more complete will be the lateral destructive interference and the smaller the amount of nonforward scattering. Thus, most of the energy will go into the forward direction, and the beam will advance essentially undiminished.

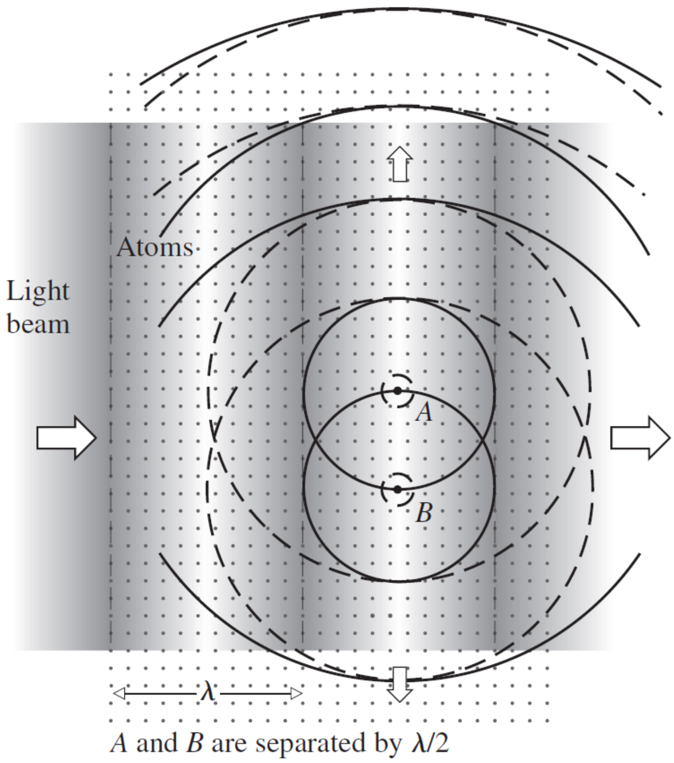

Figure 1. 3. A plane wave impinging from the left. The medium is composed of many closely spaced atoms. Among countless others, a wavefront stimulates two atoms, A and B, that are very nearly one-half wavelength apart. The wavelets they emit interfere destructively. Trough overlaps crest, and they completely cancel each other in the direction perpendicular to the beam. That process happens over and over again, and little or no light is scattered laterally.

1.2.3 Transmission and the Index of Refraction

The transmission of light through a homogeneous medium is a repetitive process of scattering and rescattering. Each such event introduces a phase shift into the light field, which ultimately shows up as a shift in the apparent phase velocity of the transmitted beam from its nominal value of **c**. That corresponds to an index of refraction for the medium,

$$\mathbf{n = c/v} \tag{1.1}$$

To explain that, we can anticipate that the secondary wave will combine with what is left of the primary wave to yield the only observed disturbance within the medium (the transmitted wave). Both the primary and secondary electromagnetic waves propagate through the interatomic void with the speed ***c***. *Yet the medium can certainly possess an index of refraction other than 1*. The refracted wave may appear to have a phase velocity less than, equal to, or even greater than ***c***. This is depended on the phase relationship between the secondary and primary waves.

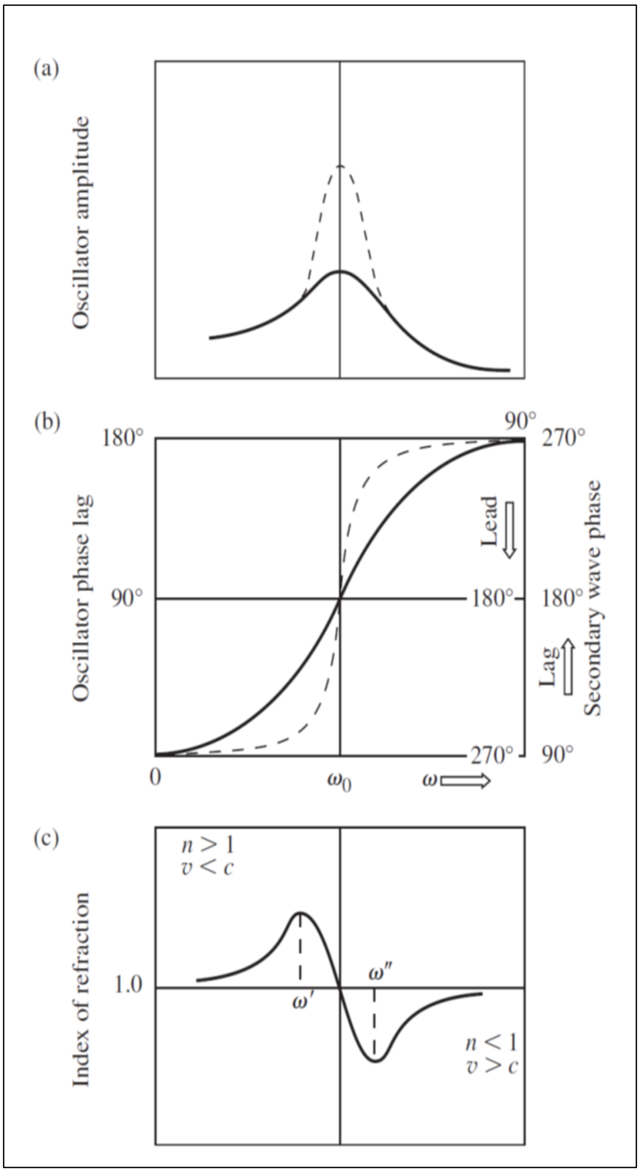

Figure 1. 5. A schematic representation of (a) amplitude and (b) phase lag versus driving frequency for a damped oscillator. The dashed curves correspond to decreased damping. The corresponding index of refraction is shown in (c).

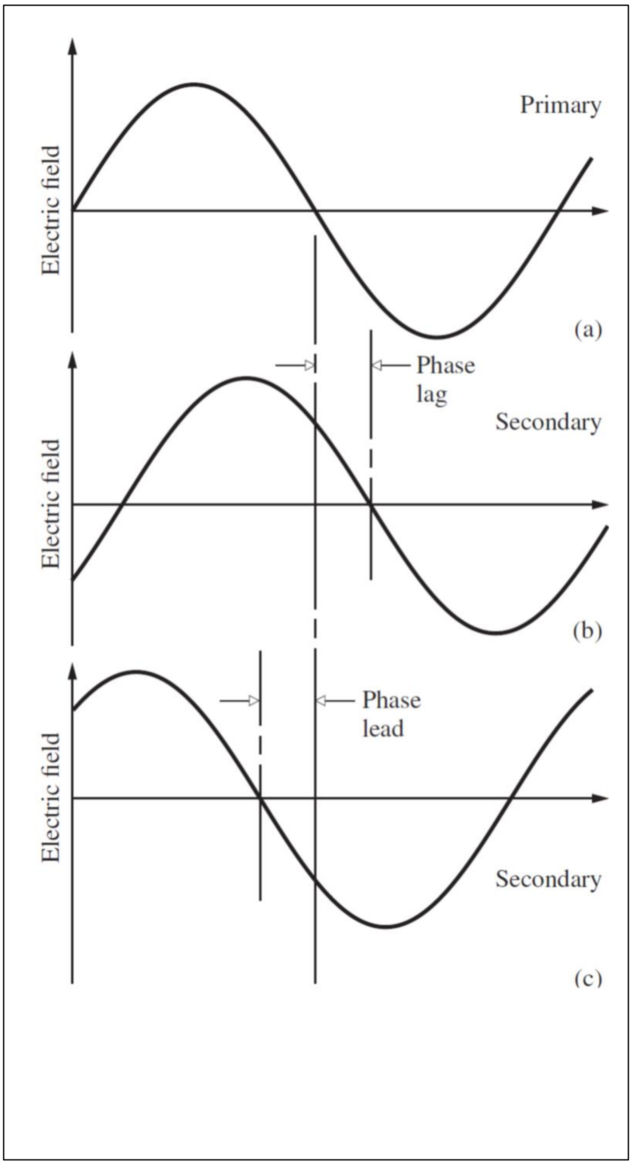

Figure 1. 4. A primary wave (a) and two possible secondary waves. In (b) the secondary lags the primary—it takes longer to reach any given value. In (c) the secondary wave reaches any given value before (at an earlier time than) the primary; that is, it leads.

proportionately larger amount. A detailed analysis reveals that at resonance the phase lag will reach 90°, increasing thereafter to almost 180°, or half a wavelength, at frequencies well above the particular characteristic value, see Fig 1.4. In addition to these lags there is another effect that must be considered. When the scattered wavelets recombine, the resultant secondary wave* itself lags the oscillators by 90°. The combined effect of both these mechanisms is that at frequencies below resonance, the secondary wave lags the primary (Fig. 1.5) by some amount between approximately 90° and 180°, and at frequencies above resonance, the lag ranges from about 180° to 270°.

When the secondary wave lags (or leads) the primary, the resultant transmitted wave must also lag (or lead) it by some amount (Fig. 1.6).

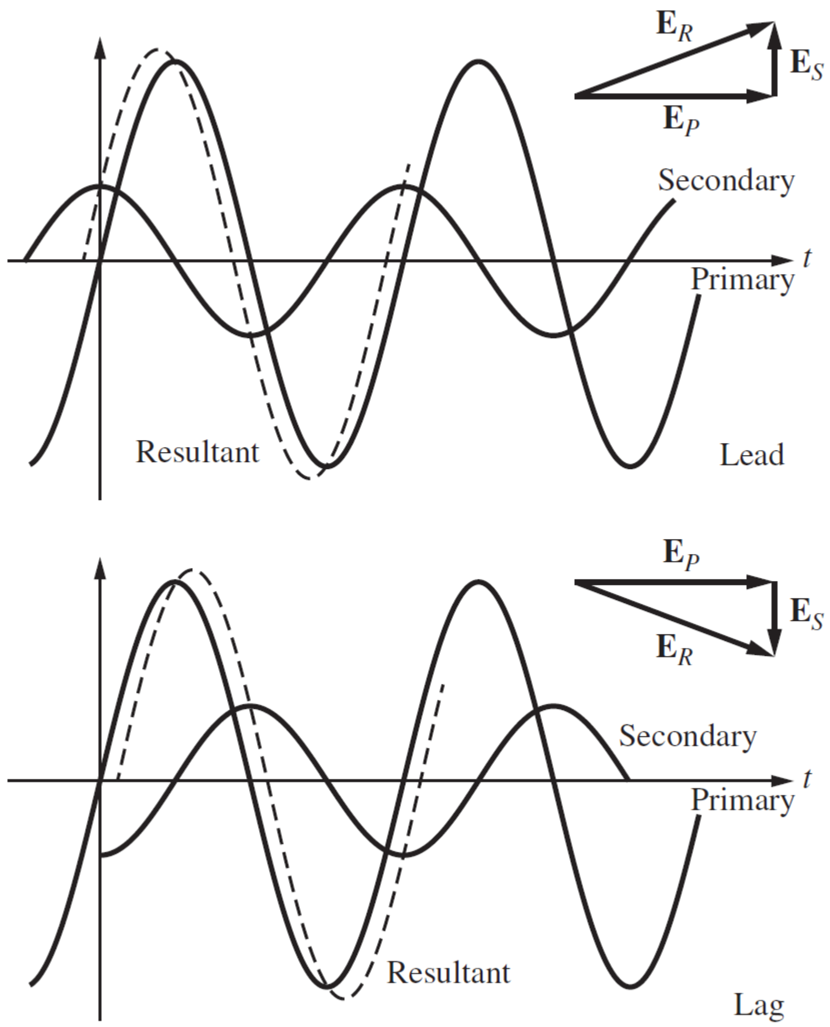

Figure 1. 6. If the secondary leads the primary, the resultant will also lead it. That point is underscored by the phasor diagrams.

References:

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2-Optics,-Eugene-Hecht
3-Optics and photonics an introduction