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"The Interaction of Acoustic Phonons and Photons in the Solid State"

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When light and sound simultaneously pass through a medium, the acoustic phonons of the sound wave scatter the photons of the light beam. This scattering of light from acoustic modes is called Brillouin scattering. More specifically, Brillouin light scattering is the nonlinear, inelastic scattering of an incident optical field by thermally or acoustically excited elastic waves. The nonlinear nature of the scattering is caused by the nonlinearity of the medium, particularly that part of the linearity expression that is related to acoustic phonons. This type of scattering occurs when an optical wave in solid or liquid medium interacts with density variations and diffracts, or changes its path. These density variations may be due to acoustic modes or temperature gradients. The first significant study of the interaction of light and sound was carried out by Mandelstam in 1918; however, he did not publish his work until 1926. Brillouin, after whom the effect is named, independently predicted light scattering from acoustic waves in 1922. Brillouin's predicted scattering was experimentally confirmed by Gross in 1930.

The interaction of acoustic phonons and photons observed in Brillouin scattering is referred to as the acousto-optic effect, a branch of the photoelastic or optoelastic effects. The acousto-optic effect allows the controlling of any number of parameters of an optical wave including amplitude, phase, frequency, and polarization.

When treating Brillouin scattering as a quantum interaction, the process is considered to be a result of the interaction of photons from the incident light beam with acoustic or vibrational "quanta" (phonons). The interaction of these photons with the associated phonons consists of inelastic scatter in which a phonon is either generated in a Stokes process or annihilated in an anti-Stokes process. While this is, strictly speaking, the most precise description of the acousto-optical effect, it is not necessarily the most useful. More commonly, a classical outlook is taken with regards to the process.

The use of the classical viewpoint rather than the quantum viewpoint is reinforced by the fact that, for a transparent solid, most of the scattering from a refracted beam emanates from a region well away from the surface towards the interior of the solid. The kinematic conditions relating wave vector and frequency shift (discussed later) of the light pertain to bulk acoustic wave scattering.

From a purely classical point of view, as a compression wave (such as sound) moves through a medium, the density of the medium will change, altering its polarity and diffraction index. In an acousto-optical crystal (a material that modifies its refractive index when an acoustic wave travels through its structure), sound waves act as if they are passing through a gas, traveling through compressions and rarefactions of the medium. Dynamic fluctuations in the strain field bring about fluctuations in the dielectric constant of the medium. The fluctuations of the dielectric constant in turn translate into fluctuations in the diffraction index. The resulting change in diffraction index alters the path of an optical beam passing through the medium. Furthermore, the fluctuating optical inhomogeneities cause a certain amount of inelastic scattering and reflection at any point at which a density gradient forms from the compression waves passing though the medium. In the regions where the medium is compressed, the density of the material is higher and the refractive index increases; in the regions where the medium is rarefied, the density of the material is lower and the refractive index decreases. For solids in particular, the compression wave produces an elastic vibration of the molecules about their equilibrium positions, changing the optical polarizability and ergo the diffractive and refractive indexes of the material.

The acoustic drive signal applied to the crystal determines whether or not light passing through a crystal is diffracted or transmitted. Therefore, as the diffraction occurs as a function of time, following the drive signal and according to the pattern defined by the acoustic wave, it is simple to created a pulsing pattern of diffracted light by altering the drive signal. Remember, the speed of light through the medium is many orders of magnitude greater than the speed of sound (both though are dependent on the material, temperature, etc), and so at every moment the light beam treats the sound wave as a standing wave, causing the crystal to act as a grating for the incoming light, diffracting the transmitted light. When the fixed-frequency drive signal is active, the light is diffracted; when the drive signal is deactivated, the light passes through without the additional diffraction. By altering the drive signal frequency, one may alter the wavelength of the density variations, which controls the angle of diffraction. Therefore, by changing the drive signal frequency, one can regulate the diffraction angle.

A particularly interesting effect of Brillouin scattering has to do with the frequency of the scattered light. An incident photon can be converted into a scattered photon of slightly lower energy, normally propagating in the backward direction, and a phonon. For a Stokes process, where a phonon is generated, the frequency of the scattered light is decreased; for an anti-Stokes process, where a phonon is annihilated, the frequency of the scatted light is increased. Increased frequency, by the equation $E = h\nu$, means increased photon energy. The difference between the energy of the scattered photon and the incident photon is called the Brillouin shift. The shift energy is equal to the energy of the interacting phonon. Furthermore, the frequency of the incident photon is the frequency of the generated phonon and visa versa. Ultimately, the Brillouin frequency shift, as restrained by a phase-matching requirement, depends on the material composition, the incident optical frequency, and, to a degree, the temperature and pressure of the medium.

The Brillouin shift can occur spontaneously, even at relatively low optical power-densities. However, above a certain power threshold of a light beam passing through a given medium, the shift may become very strong stimulated effect. Above this threshold, the Stimulated Brillouin Scattering can "reflect" the majority of the power of the incident optical beam, a process requiring a dominant nonlinear optical gain for the back-reflected wave.

When a particularly intense beam of light travels through a medium (high photon count), the irregularities in the electric field component of the electromagnetic beam can cause phonons to be produced in the material by electrostriction. As a result, the incident beam may undergo Brillouin scattering from the self-caused acoustic vibrations. This is Stimulated Brillouin Scattering. The scattering is normally directed in the opposite direction of the incident beam. This is one possible means by which phase conjugation may occur. The phonons present in the medium move in thermal equilibrium with very tight vibrations. This causes the aforementioned dielectric constant fluctuations, which in turn acts as a mobile diffraction grating by the optical wave. Mathematically, Stimulated Brillouin Scattering can be explained by Bragg reflection and Doppler shift.

Though normally applied to X-ray diffraction, Bragg's Law is strongly relevant in Brillouin scattering. According to Bragg's Law, the grating spacing *d* created by the acoustic phonons may be given in terms of the Bragg angle ($\varphi/2$) and wavelength of the laser light inside solid $\lambda = \lambda_0/n$, where λ_0 is the laser wavelength in a vacuum, and n is the index of refraction in the solid. This gives the equation

$$2d \sin(\varphi/2) = \lambda_0/n$$

In the Doppler shift, the mobile diffraction grating set up by the acoustic wave scatters the incident optical beam with a Doppler effect, resulting in scattered photons with offset frequencies Δf. The Brillouin spectrum gives the frequency shift (Δf) of the acoustic phonon; its wavelength (d space) can be determined from the experiment geometry. This gives a phonon velocity V_l of the form

$$V_l = \lambda_0 \, \Delta f \, / \, [2n \sin(\varphi/2)]$$

A simplified expression is created by setting $\varphi = \pi$, where the equation becomes

$$V_l = \lambda_0 \, \Delta f \, / \, (2n)$$

The concepts outlined here are already applied in areas such as fiber optics (acousto-optical modulators and Q-switches), Brillouin microscopes, and thermal imaging. An interesting possible area of application is that of microwave sintering of nuclear fuels.

Microwaves are used in the heating of nuclear fuels, with a process similar that that occurs in a common household microwave, where the heating is a result of dielectric breakdown. The microwaves causes the dielectric constant of the material to flip on and off. Recall that, in Brillouin scattering, the dielectric constant of the material is altered. This brings several questions to the fore.

- The most common microwave frequency used in sintering is 2.45 GHz, which is also an acoustic frequency. How would a concurrent acoustic wave, either injected into the system or set up by the presence of the incident beam's electric field, affect the heating gradients in the material?
- Is the change in the dielectric constant as a function of the microwave power density a quantifiable value? To this end one would need to determine the half power depth of penetration of the microwaves, where half power depth is defined as the depth at which the power density is one half of what it is at the surface.

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