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LASER-ULTRASONIC INTERACTION AND LASER INVESTIGATION OF PHONON BEHAVIOR VIGOROUS NEW FIELDS OF NON-LINEAR OPTICS

Definitions and Fundamental Theory

Phonon. A phonon is a sound quantum and bears the same relation to a quantized sound wave as does a photon to a quantized electromagnetic wave. The term is chiefly used in connection with the vibrations of the atoms in a crystal where the sound waves are the normal modes of vibration of the lattice.

If ω is the angular frequency and q the wave vector of the corresponding normal mode, the energy of the phonon is $\hbar\omega$ and its velocity is given by the group's velocity grad ω. The quantity $\hbar q$, the so-called quasimomentum, differs from ordinary momentum in being physically unchanged when a vector equal to 2π times a reciprocal lattice vector is added to the vector q.

The phonons of a crystal with pure harmonic forces do not interact with each other. Anharmonic forces, however, give rise to collisions between the phonons and hence bring about thermal equilibrium of the phonon gas, i.e., equilibrium for the thermal motion of the lattice.

The relation between the frequency and wave vector of the phonons in a cry-stall may be determined by measurements of the inelastic scattering of neutrons or X-rays.

Phonon Scattering. The thermal motion of atoms in a crystal may be regarded as a set of phonons or sound quanta travelling through the lattice. The phonons do not travel freely but are scattered, owing to: a) interactions with each other due to the anharmonic component of the interatomic forces, b) the presence of isotopes, c) impurities, d) various types of lattice imperfection, and e) the finite size of the crystal. In a metal, the electric forces between the nuclei and the conduction electrons provide a further source of phonon scattering. We consider first the anharmonc effect, i.e. phonon-phonon scattering.

Anharmonic forces give rise to terms in the potential energy in the third and higher powers of the displacement of the atoms from their equilibrium positions. The cubic term causes scattering processes in which three phonons are involved. Either two phonons are destroyed and one created or vice-versa. The wave vector $\vec{q}_1$ and $\vec{q}_2$ of the two phonons are related to the wave vector $\vec{q}_3$ of the third by the equation

$$\vec{q}_1 + \vec{q}_2 = \vec{q}_3 + 2\pi \vec{\tau}$$

where τ is a vector in the reciprocal lattic; collisions in which τ is not zero are known as "Umklapp" processes and it is these processes which give rise to thermal resistance.

At temperatures low compared with Θ, the Debye temperature, most of the phonons that make up the thermal motion have values of $\vec{q}$ too small to satisfy the above equation except for $\tau = o$. It has been pointed out that in this temperature region the thermal resistance of a dielectric crystal is governed by the small number of phonons that can give rise to Umklapp processes. The energy of such phonons is of the order of $(1/2)(K\Theta)$ where K is Boltzmann's constant. Thus the thermal resistance of dielctric crystals at low temperatures may be expected to vary as $\exp{-\Theta/2T}$. A variation of this form has been found, for example, in solid helium. At high temperatures the analysis of phonon-phonon scattering is complicated.

Other causes of phonon scattering have also been studied theoretically and experimentally. Changes in the thermal resistance due to lattice defects and crystal size have been observed. The presence of isotopes, giving a random variation in the masses of the atoms is an important cause of phonon scattering and may considerably increase the thermal resistance.

In a metal, the phonons and conduction electrons interact strongly. At each collision a phonon is created or destroyed. At low temperatures, phonons are strongly scattered by electrons that they contribute very little to the heat conduction, nearly all of which is due to the electrons.

The scattering of the conduction electrons by phonons is mainly responsible for the electrical resistance of a pure metal. The scattering results in a resistance which at $T \ll \Theta$ varies as T^5, and at $T \gg \Theta$ varies as T.

Debye Temperature. By considering a monatomic substance as a homogeneous, isotropic, elastic medium, the heat energy of which was equivalent to the energy of 3N elastic waves varying in frequency from zero to ν max, Debye derived an expression for heat capacity containing $h\nu/K$ (K= Boltzmann's constant). For each substance $h\nu_{max}/K$ has a special value called the characteristic or Debye temperature Θ. At low temperatures $C_v = 464.5\ (T/\Theta)^3$ whence $\Theta = .129\ C^{1/3}/T$.

Although Debye's assumptions are not valid, and $C_v^{1/3}/T$ is not independent of temperature, numerical values of "Debye Θ", are often used to describe approximately the slope of the curve of C as a function of T.

Objective. 1) To construct a versatile ultrasonic source, 2)a - To investigate the direct interaction of laser light and ultrasonic energy occuring in various types of light scattering -b- To investigate phonon behavior in plexiglass, etc., involving a study of light interaction with paramagnetic spins.

Unfortunate Ephemeral Expections. The effect of intense spatially and temporally coherent light on ultrasonic wave motion should have provided an opportunity to observe light amplification by many orders of magnitude, without the negating effects of noise; inherent to many amplifying systems (phototubes and scintillation counters). The fleeting opportunity to observe this amplification was to be initiated by an ultrasonic spectrum analysis (not unlike light spectrum analysis of heated gases or incinerated solids) and hopefully the use of different polarizations of light.

The amplification takes place (theoretically) as a result of information about the test material's phonon structure (plexiglas, crystals, etc.) being put on light passing through the test material. Visualizing AM or FM modulations in the commercial radio field would be helpful in this connection. However, rather than interacting directly with the phonons the light interacts with paramagnetic spins which in turn mixes with the ultrasonic energies.

Accomplishments. Although stray internal capacitance effects within the electrical circuitry proved detrimental to the expected versatility; an ultrasonic energy source was constructed. The electrical efficiency of the transistorized radiator was derived from a class "C" operation, with no harmonic nor over-driven distortion in the output energy. The pure sinusoidal ultrasonic energy wave had an amplitude of 40 V peak-to-peak with 20 V dc input B+ to the amplifier stage. And an input energy wave of 5 V peak-to-peak.

The output was measured by two methods (1) direct electrical coupling to an oscilloscope of the ultrasonic transducer at the transistor's collector and (2) by use of a simply constructed hydrophone immersed in mineral oil and approximately 5 cm from the ultrasonic transducer radiator. It should be noted that precautions were made to make sure that the ultrasonic energy was not transmitted through the walls of the mineral oil container and thus to the hydrophone.

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