B. Ya. Zel'dovich and V. V. Ragul'skii. *Wave-front inversion in induced light scattering.* One characteristic feature of induced light scattering is the high directivity of the scattered radiation. It was observed already in 1965 that the divergence of the radiation scattered in induced Mandel'shtam-Brillouin scattering is about the same as the divergence of the exciting light.[1] A similar result was later obtained for Rayleigh[2] and Raman[3] scattering. The high directivity of the scattered light was usually explained by geometric factors, and the question of a relation between the wave fronts of the exciting and scattered radiation was not raised for some time. The problem was first formulated in 1972 at the P. N. Lebedev Physics Institute.[4] It was found that inversion of the wave front may occur on induced scattering of light (Fig. 1). In this effect, the wave front of the backscattered radiation coincides exactly in shape with the exciting-light front, but the phase shifts at these fronts are of opposite signs. In other words, a phase lead gives way to an equal phase lag and vice versa in induced scattering.

Figure 1 shows a schematic diagram of the experiment that made observation of this effect possible. Radiation from a ruby laser with a nearly planar wave front (with the diffraction divergence) was passed through a spatially inhomogeneous phase plate. The wave front was strongly distorted as a result, and the divergence of the light increased by a factor of ≈25. This light entered a condensed medium (compressed gas in the first experiment), where induced scattering was excited. The divergence of the backscattered light was just a great as that of the exciting light; however, after passage back through the phase plate, the divergence of the scattered light was much smaller and comparable to the divergence of the original laser beam. Figures 2(a) and 2(b) show the angular distributions of these beams; they coincide at the diffraction level. Calorimetric measurements indicated that 26% of the laser radiation was scattered in this experiment. Photometry of the negatives in Figs. 2(a) and 2(b) showed that the brightness of the scattered radiation after passage through the plate is also 26% of the brightness of the original laser light. Therefore the wave front of the scattered light was fully "corrected" on passage through the phase plate. The scattering medium was replaced by a plane mirror in a control experiment. In this case the reflected radiation passing back through the plate was not "corrected" at all, but, to the contrary, was distorted further [Fig. 2(c)].

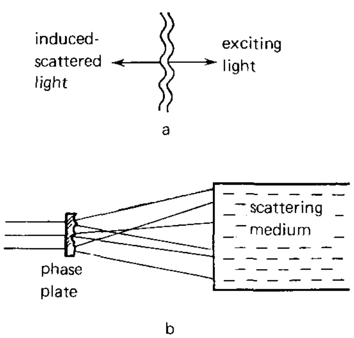

FIG. 1. Correlation between wave fronts of exciting and scattered light (a) and diagram of experiment to observe it (b).

The results described above indicate that the wave front is inverted on induced scattering. In fact, suppose that the laser field has the form $E_L(r)$, where $r \equiv (x, y)$ are coordinates perpendicular to its propagation direction. Then the exciting-radiation field has the the form $E_0(r) = E_L(r)e^{i\varphi(r)}$, where $\varphi(r)$ is the phase shift introduced by the plate. The scattered field $E_s(r)$ after passage back through the phase plate acquires the same phase shifts and has the form $E_1 = E_s e^{i\varphi}$. It follows from the agreement of E_1 with E_L that $E_s \sim E_L e^{-i\varphi}$, i.e.,

$$E_s(r) = \text{const}\, E_0^*(r). \qquad (1)$$

The implication of this equation is precisely that inversion of the wave front occurs. The effect comes

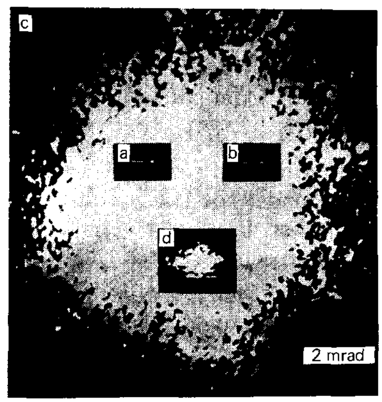

FIG. 2. Far-zone distribution patterns: laser radiation (a); backscattered radiation passed through phase plate (b); light reflected by plane mirror (c); scattered light in absence of phase plate (d).

about on scattering of radiation with a spatially inhomogeneous intensity distribution. However, if the intensity of the exciting light varies little along the transverse coordinates, there is no inversion [Fig. 2(d)].

The first paper was followed by experimental and theoretical studies that established features of the wave front inversion phenomenon and determined the limits within which it exists (see, for example, Refs. 5–11). It was found that this phenomenon occurs in a broad range of conditions. It is observed in various experimental geometries on scattering of both small (<1%) and large (>50%) fractions of the exciting radiation and at small and large (much larger than the spontaneous scattering linewidth) spectral widths of this radiation. The effect is insensitive to frequency variation for scattering in the range from $\Delta\nu/\nu \sim 10^{-5}$ (Mandel'shtam-Brillouin scattering) to $\Delta\nu/\nu \sim 10^{-1}$ (Raman scattering). A number of other parameters may also be varied.

Theoretical analysis enabled us to understand the nature of this phenomenon. It is based on the extremely high amplification required for development of spontaneously scattered photons in a strong scattered wave. Under typical observing conditions, the amplification $=\exp(Gl) \sim 10^{10}$, where G is the gain (in cm^{-1}) and l is the interaction length. As a result of this high amplification, even modest (of the order of unity) relative variations of G influence the characteristics of the scattered field extremely strongly. A quantitative treatment can be given within the framework of the parabolic equations

$$\frac{\partial E_0}{\partial z} + \frac{i}{2k_0}\Delta_\perp E_0 = 0, \tag{2a}$$

$$\frac{\partial E_s}{\partial z} - \frac{i}{2k_s}\Delta_\perp E_s = \frac{1}{2} g |E_0|^2 E_s, \tag{2b}$$

where k_0 and k_s are the wave numbers of the exciting and scattered radiation; the z coordinate increases in the propagation direction of the scattered field. In Eq. (2b), the constant g describes the local amplification of the scattered field due to pumping. Its numerical value is determined by the specific scattering mechanism and by the characteristics of the medium. Analysis of these equations shows that the gain is determined for scattered waves of various configurations by the expression

$$G = \frac{g\int |E_0(r,z)|^2 |E_s(r,z)|^2 dr}{\int |E_s(r,z)|^2 dr}. \tag{3}$$

By virtue of (1), the local intensity maxima of $|E_s|^2$ for the scattered wave with inverted wave front coincide everywhere in the interaction volume with the maxima of $|E_0|^2$. However, this coincidence cannot occur for waves of other configurations (uncorrelated with the pump). Equation (3) therefore indicates that the gain is higher for the inverted wave than for any other.

When a large number of interference maxima and minima are present in the exciting field, the gains for a wave with an inverted front and for waves uncorrelated with E_0 differ by a factor of two:

$$G_{\text{inv}} = 2G_{\text{uncor}}. \tag{4}$$

As a result, the power of the inverted component is $\sim 10^5$ times greater than the power of the other components on emergence from the medium. If, therefore, there are fewer than 10^5 of them, the inverted component in the scattered field will not only exceed all other components in brightness, but will also carry practically all the energy of the scattered field.

Noninversion of the wave front for an exciting field whose intensity varies little over its cross section can also be understood from (3). In this case, $|E_0|^2$ can be taken out from under the integral sign, so that the gains are equal for all waves.

The properties of solutions of the system (2a), (2b) have now been studied in detail. They have yielded, for example, admissible values of the angular divergence, frequency shift, and interaction length at which wave front inversion occurs.

This effect can be used to build a number of optical systems that could not be devised with the tools of classical optics. For example, it becomes possible to design a system with a master laser generator and an optically inhomogeneous amplifier—a system that can convert the energy stored in the amplifier into a beam with the ideal (diffraction) divergence. The idea of the method is to pass the diffraction-quality beam from the generator through the inhomogeneous amplifier and then subject it to induced scattering with wave front inversion. The scattered wave would be passed through the same amplifier, which can be treated as a distributed analog of the phase plate, be amplified, and its front "corrected" to practical planarity. This program has been carried out experimentally.[12]

The phenomenon of wave front inversion can also be used to aim laser radiation automatically at its target; through a turbulent atmosphere,[13] at a laser-fusion target,[14] and when optically inhomogeneous amplifiers and optical trains with aberrations are used. The idea is first to illuminate the target with a broad beam from another laser. Thus the target becomes a source of secondary waves. A certain (small) fraction of the energy of these waves enters the aperture of the power laser system. The radiation arriving from the target would be amplified in the power stages of the laser system, subjected to wavefront inversion, and passed again through the same amplifiers. The radiation from the power amplifiers would then be delivered to the target as though it had undergone aberration-free focusing with diffraction precision. The problem of accurate aiming of the laser radiation at the target is also eliminated as a bonus. The prospects opened up here are so intriguing that progress may be expected from the research now being done in this area.

Note in proof. The above principle of automatic aiming at the target was realized soon after this paper appeared. It has been shown experimentally[15] that it does indeed ensure incidence of practically all the radiation on the target irrespective of the latter's position in space and of aberrations present in the optical elements.

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