NONLINEAR OPTICS AND ADAPTIVE LASER SYSTEMS

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Nova Science Publishers, Inc.

ACADEMY OF SCIENCES OF RUSSIA
Institute of Applied Physics

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Translated from Russian
by Gia Tsitsuashvily

Nova Science Publishers, Inc.

Art Director: Christopher Concannon
Graphics: Elenor Kallberg and Maria Ester Hawrys
Book Production: Michael Lyons, Roseann Pena,
Casey Pfalzer, June Martino,
Tammy Sauter, and Michelle Lalo
Circulation: Irene Kwartiroff, Annette Hellinger,
and Benjamin Fung

Library of Congress Cataloging-in-Publication Data

Bespalov, V.I. (Viktor Ivanovich)
[Nelineinaia optika i adaptivnye lazarnye sistemy. English]
Nonlinear optics and adaptive laser systems / V.I. Bespalov and G.A. Pasmanik
p. cm.
Translation of: Nelineinaia optika i adaptivnye lazarnye sistemy.
Includes bibliographical references and index.
ISBN 1-56072-121-9 : $77.00
1. Nonlinear optics. 2. Lasers. I. Pasmanik, G.A. (kGerman Aronovich). II. Title.
QC446.2.B4713 1993 93–38278
621.36'6--dc20 CIP

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Printed in the United States of America

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PREFACE

The monograph deals with certain problems in nonlinear optics with reference to the problem of development of laser systems with wavefront reversing (WFR) mirrors. The authors seek to form the reader's general concept of physics of corresponding processes, to give a graphic interpretation of their features and present analysis methods which help estimate the usefulness of various nonlinear optical effects (stimulated scattering, three- and four-wave interactions) for creation of WFR mirrors with desired parameters and also to make an optimal choice of nonlinear materials.

Chapter 1 of this treatise presents principal relationships pertaining to stimulated light scattering, and in Chapter 2 three- and four-wave interactions are discussed. In both chapters the consideration is purposefully conducted as applied to the problem of WFR (wavefront reversal) as well as to some other problems of correction of light beams' space-time structure. Among them are the problems of electromagnetic wave field phase multiplication, radiation frequency transformation with preservation of its spatial structure, energy transfer from a high-power but non-directional light beam to an initially weak but directional light beam, the problem of laser pulse shortening in processes of nonlinear transformation, etc.

Chapter 3 of the book is devoted to the discussion of concrete adaptive laser systems. There, processes in double-pass amplifiers with WFR mirrors are analyzed and given are the results obtained for the brightness of optical radiation. Considerable attention is also given to the analysis of the operation of laser systems with adaptive focusing of radiation on a target. Besides, there are also discussed the peculiarities of self-excitation of lasers with WFR mirrors and problems of adaptive processing of optical information, in particular, the problem of separation of low-level optical signals from noises with the help of nonlinear wave processes and registration of their space-time structure.

The authors did not have a chance to cover consistently all those problems of the theory of nonlinear processes which are related to the problem of WFR in nonlinear media and in some cases give only final relationships with references to the sources where due calculations may be found. By the time the present book was completed, plenty of articles (over 500) have been published on the problem of WFR in nonlinear media. A rather full list of papers on this subject (through 1982) is available in the collected volume "Radiation wavefront reversal in nonlinear media" edited by V.I.Bespalov (Gorky, IPF AN SSSR, 1982, 247 pp.). This is why the authors give a minimal number of necessary references and mainly those of other researchers whose results are used in this book.

In view of the problems under discussion, readers may want to become acquainted with some aspects of WFR radiation based on the use of coherent adaptive optical technology. If so, they may be referred to the list of references in "Adaptive Optics" edited by E.A. Vitrickhenko (Moscow, Mir Publishers, 1980, 456 pp.). Certain problems associated with the influence of nonlinear wave processes on the path of light beam propagation exerted over the operation of adaptive laser systems are discussed in the review article "Thermal self-action of light beams and methods of its compensation" by S.A. Akhamanov, M.A. Voronstov, V.G. Kandidov, A.P. Sukhorukov and S.S. Chesnokov (isv. Vusov, Radiofizika, 1980, vol. 23, No. 1, pp. 5-38).

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Introduction

Directivity of laser radiation is its most important characteristic. Improvement of directivity, or decrease of light beam divergence, leads to the increase of the operating range of laser beam communication lines, optical range finders, etc. Decrease of divergence is especially important in cases when it is necessary to achieve the highest concentration of optical energy or power on targets with small angular dimensions due to the small area of their surface or to their remoteness from the radiation source.

Minimal divergence of a light beam of diameter D_O is bounded by the so-called diffraction limit given by the approximate relation $\theta_D = \lambda_O / D_D, \lambda_O$ being the radiation wavelength. However, the real divergence of a laser beam is close to the diffraction divergence only when the surface of its wavefront is plane. Generally, light beams of small diameters easily make a plane wavefront surface. But when their diameters increase, difficulties in forming beams with extremely small (diffraction) divergence rise drastically. This is due to the impossibility of production of perfect (aberrationless) optical elements as well as to alteration of the properties of these elements as they are traversed by laser radiation during the processes of its generation, amplification and transformation for the subsequent use.

A most difficult problem to solve is to produce a plane wavefront of high-energy and powerful light beams. To compensate the time-variant distortions of the laser beam wavefront surface (such as those occurring during the process of amplification), a number of methods were put forward in the late 60s and early 70s for the correction of the transverse structure of optical radiation which are based on the use of nonlinear optical processes. From that time on, nonlinear optics is having ever-increasing influence on the development of new lasers. In consequence, by the early 80s, the principles were worked out for the construction of lasers insensitive to the optical quality of the used elements. New generation lasers incorporate devices which utilize nonlinear wave transformations of light beams. Specifically, a record brightness of optical radiation has been achieved by means of this kind of lasers.

Nonlinear wave transformations ensure the correction of light beams that leads either to the formation of a plane wavefront of the outgoing laser radiation or to the transmission of this radiation through a inhomogeneous medium to a given aperture with minimal diffraction losses of power. The gist of this correction is that the light beams formed in the process of laser oscillation align with the optically non uniform path along which they run. This is why lasers based on this kind of correction are called adaptive lasers.

For the correction of the transverse structure of optical radiation, wavefront reversal (WFR) is used. During WFR, a reversed light beam is formed in which all the spatial distributions of the transverse structure of the initial (forward) wave are reproduced in reverse order as the light beam travels. We can say that the WFR process is equivalent to reflection from a kind of a mirror every surface element of which is perpendicular to the ray incident on it. If the radiation wavefront surface varies in time, then such a mirror must also vary the shape of its surface adjusting every time to the radiation incident on it.

Light WFR in nonlinear media is based on different types of stimulated scattering, first of all on the stimulated Brillouin scattering (SBS) and the processes of three- and four-wave interaction of light waves.

Processes of nonlinear interaction of light waves that lead to WFR are realized in media with quadratic and cubic dependence of the substance's nonlinear polarization upon the light wave field amplitude. They are called three-wave processes for quadratic media, and four-wave processes for cubic media. For the realization of WFR, quadratic or cubic media are exposed to one or two (opposing) waves, respectively (they are called reference waves in holography, and pumpings in nonlinear optics). Apart from that, the nonlinear medium is also exposed to a so-called object, or signal, wave the wavefront of which is to be reversed. Upon the interaction of reference and object waves, a new wave is excited on account of the nonlinear polarization of the medium.

For WFR in quadratic media, the frequency of the reference wave is chosen to be twice as high as the frequency of the object wave. In such case, the "newborn" wave travels at the same angle as the object wave with respect to the reference wave but in the mirror symmetrical direction. If behind the nonlinear medium there stands a plane mirror perpendicular to the reference wave, then a wave excited during the three-wave interaction is reflected from it and changes the direction of its propagation so that it becomes almost reversed with respect to the initial object wave.

For the interaction of waves in cubic media, the frequencies of the reference and object waves are taken to be close to each other. In this case, the excited new wave runs in the direction opposite to that of the propagation of the object wave and has a reversed (with respect to this wave) wavefront.

In both discussed cases, energy is transferred from the reference waves to the reversed wave. The reflection factor R, equal to the ratio of the powers of the reversed and initial (object) waves, may come up to values far greater than unity. Parametric methods are marked by their being "thresholdless", that is, the reflection factor weakly depends on the object wave's amplitude.

For the realization of WFR based on stimulated scattering no reference waves are really needed. Here occurs the so-called wavefront self-reversal. For these purposes, the SBS process is most widely used nowadays. In this process, a spatially inhomogeneous pumping wave subjected to WFR creates a non uniform gain profile for the opposing wave (shifted by the hypersound frequency to the Stokes region). Initially, a Stokes wave is born as a result of spontaneous scattering of the pumping wave and then it is amplified in the non uniform gain profile with local increment proportional to the incident wave intensity. The part of a Stokes wave, spatial splashes of intensity of which fall within the regions of maximum gain (i.e. the regions of largest values of the pumping wave intensity), builds up with the highest rate. As a result, the opposing wave turns into a wave with a reversed wavefront and the spatial field structure that reproduces (with complex conjugation) the pumping wave field.

We can take a different look on the WFR phenomenon in SBS. In the process of interaction of the incident pumping wave and the opposing Stokes wave in the nonlinear medium, there is excited such a hypersound wave of complex structure that the radiation reflected from it runs strictly backward, in the direction of its arrival. The hypersound wave plays in this process the role of a moving flexible WFR mirror created by the light itself. Since the above-mentioned light wavefront self-reversal takes place during stimulated scattering, the reflection factor here is always less than unity.

Owing to ease of realization and thorough studies of them, the above nonlinear processes have found wide application in modern optics for the correction and formation of laser radiation structure. They have helped to resolve the problem of compensation of aberrational distortions brought into light beams by real optical elements, to improve the directivity of laser radiation, increase its energy and enhance its brightness.

Light WFR in real time makes it possible to create systems of adaptive focusing of radiation on a target. Such systems are based on preliminary illumination of the target by non directional radiation, amplification and reflection with WFR of the light scattered by the target. One of the key moments of the operation of such systems is the realization of WFR of very low-power light signals. In doing this, it is important to reach the limit when the quantization of optical fields imposes fundamental restrictions on the feasibility of the reversal of their wavefronts.

Much promise is also offered by methods of excitation between a target and a radiation source of a (adaptive) light beam self-adjusting to an optically inhomogeneous path, being corrected so as to ensure optimal transfer of laser pulse energy to the target. Such a beam may be formed when the target and the WFR mirror (or two WFR mirrors optically connected via the target) make up an adaptive resonator self-excitation of which leads to the generation of radiation focused directly on the target. Realization if such generation is of particular interest when the resonator with WFR mirrors has heavy diffraction losses.

1

STIMULATED SCATTERING OF LIGHT

1.1. Physical outlines and principal features of stimulated scattering

1.1.1. The nature and classification of different kinds of stimulated scattering

Optical radiation which passes through a macroscopically homogeneous medium, i.e. a material without the so-called technical inhomogeneities that are due to the specificity of its creation, is scattered by the time-variant inhomogeneities of the refractive index Δn brought about by fluctuation processes always going on not only in gases and liquids but in solids, too. This kind of scattering is called spontaneous scattering (SpS). It is induced by thermal motion of particles, rotational or oscillatory molecular motion and lattice vibrations and is, as a rule, so weak that goes unnoticed; its intensity is proportional to the intensity of the light traversing the medium. But such proportionality is relevant only up to a certain level of power of the light incident on the medium, and above this level a faster growth of scattered radiation takes place, and spontaneous scattering becomes stimulated scattering (SS). The intensity of the latter may be so high that the incident light may entirely turn into scattered light. The change of the type of scattering is caused by the fact that at rather high intensities of radiation the initially weak (spontaneous) fluctuations of the refractive index are built up thanks to the interference of the incident and scattered light. This results in the change of the intensity as well as of the space-time spectrum of these fluctuations. In consequence, the scattering factor increases and the space-time structure of the scattered radiation changes, too. The last circumstance is very important for, it makes it possible to use SS for the transformation of light beams incident on a nonlinear medium, which is essential, in particular, for the solution of problems in adaptive optics.

There are many types of SpS and, SS respectively associated with different processes in nonlinear media. But not all kinds of SS are easy to be registered and even more so to be used primarily because of their concurrence as well as of the presence of other nonlinear processes, (such as breakdown, self-focusing, multiquantum light absorption, etc.). In this connection, not all kinds of SS are of equal interest for the problem in question and not all of them will be considered below. One or other type of SS will be given preference to suit the conditions of experiment (or of a problem under study).

Fluctuations Δn_{ij} of the refractive index have, in general, the isotropic Δn and the anisotropic $\Delta n'_{ij}$ components:

$$\Delta n_{ij} = \Delta n \delta_{ij} + \Delta n_{ij}', \tag{1.1}$$

where $\Delta n = \sum \Delta n_{ii}$. Hence,

$$\Delta n'_{ij} = \Delta n_{ij} - \delta_{ij} \Delta n \left(\sum_i \Delta n'_{ii} = 0 \right).$$

The Δn are brought about by thermodynamic fluctuations of the isotropic characteristics of media. Scattering resulting from the variation Δn caused by perturbations of pressure ρ is called the Brillouin scattering whereas scattering stemming from the variations Δn caused by perturbations of entropy S is said to be the entropy (temperature) scattering. If the medium is a solution or a mixture of gases or liquids, then the variations Δn of the refractive index may be bound up with fluctuations of concentration, and hence we have the concentration scattering. Fluctuations Δn may also be induced by intramolecular motion, lattice vibrations, etc. The corresponding vibrations are called optical phonons, and the scattering on them is referred to as the Raman scattering.

The anisotropic part $\Delta n'_{ij}$ of fluctuations depend on fluctuations of parameters which characterize anisotropy. In simplified and most elaborated models of liquids and gases, such a parameter is the so-called anisotropy tensor ξ_{ij}. Usually this tensor characterizes the orientation of molecules. For example, in a medium with anisotropically polarizable or polar molecules, $\xi_{ij} = 5/2\left(<\cos\theta_i \cos\theta_j> - 1/3\delta_{ij}\right)$, where θ_i is the angle of the molecule's axis with the i-th coordinate axis, and the averaging is over the molecules within the volume element under consideration. Scattering of light by anisotropic fluctuations is called the Rayleigh line wing scattering.

Not all kinds of SS are mentioned here, but other sorts of SpS can be matched by the corresponding types of SS. At the same time, one may sometimes be faced with some extraordinary anomalies in light scattering processes when studying interactions of intensive light with the material. They are often called forth by interference of different types of SS, especially in such media as, for example, quinoline or nitrobenzene, the molecules of which are strongly anisotropic. Anomalies in light scattering are sometimes associated with the presence in the material of foreign microbodies, impurities of chemically active compounds, etc. Such anomalies are not yet adequately studied and will not be considered here.

The frequency spectra of spontaneous and stimulated scatterings are immediately related to the spectrum of fluctuations Δn_{ij} of the refractive index. If the fluctuations Δn_{ij} are expanded into a space-time Fourier integral every harmonic of which is characterized by frequency Ω and wave vector **q**, or in other words, varies as *exp (iΩt-iqr)* then it can be easily seen that a plane monochromatic wave with frequency ω_0 and wave vector k_0 is scattered by each Fourier harmonic ("grating") into a wave with the frequency

$$\omega_1 = \omega_0 - \Omega \tag{1.2}$$

and the wave vector

$$\mathbf{k}_1 = \mathbf{k}_0 - \mathbf{q}. \tag{1.3}$$

When the dispersion relations $/k_{0,1}/ = \frac{\omega_{0,1}}{c} n(\omega_{0,1})$ are fulfilled, equations (1.2) and (1.3) reflect the conditions of resonance conversion of the incident radiation into a scattered wave (the synchronism conditions). They imply that only the fluctuations, the space-time spectrum of which comprises harmonics satisfying conditions (1.2) and (1.3), contribute to the scattered light with frequency ϖ and wave vector k_i.

The Brillouin, temperature and concentration scatterings occur on relatively low-frequency fluctuations Δn (frequencies of the order of 10^{10} Hz or lower). This is why the shift or broadening of the scattered light frequency spectrum relative to the line of the incident radiation is rather small. The frequency spectrum of the Rayleigh line wing scattering is also localized near the incident radiation frequency (within the range from 10^{11} to 10^{12} Hz). Light scattering with a comparatively small shift or broadening of the frequency spectrum is customarily called the Rayleigh scattering.

The Raman scattering spectrum, unlike the Rayleigh spectrum, is shifted fairly much ($\sim 10^{13}$-10^{14} Hz) because of high frequencies of optical phonon vibrations.

1.1.2. Initial equations

Theoretical analysis of the light SS process in the general case is quite intricate and awkward, and that is why we shall hereinafter confine ourselves to the consideration of a number of simple models and, with their aid, ascertain the main features of the processes of our interest. For more complex cases we shall give only the final results and restrict the discussion by their qualitative analysis.

The optical radiation incident on the material and initiating SS is usually a laser radiation with small angular spread. To observe SS, this radiation (propagating, for definiteness, along the z-axis) is focused into the medium or passed through it without focusing. Under these conditions, it is required to determine the complex amplitude $\mathcal{E}(z=L, r_\perp, t)$ of the field of a laser beam passed through the medium, and the complex amplitudes $\mathcal{E}_s$ $(z=L, r_\perp, t)$ or $z=0, r_\perp, t)$ of the input scattered light field.

For the initial equations Maxwell's equations are taken for the fields **E** and **H** the induction vectors **D** and **B** . In an isotropic medium in the CGS electrostatic system of units these equations have the form

$$\partial \mathbf{D}/\partial t = c \operatorname{rot} \mathbf{H}, \qquad \partial \mathbf{B}/\partial t = -c \operatorname{rot} \mathbf{E},$$
$$\operatorname{div} \mathbf{B} = 0, \qquad \operatorname{div} \mathbf{D} = 0. \tag{1.4}$$

Taking due account of the fact that for the optical range of wavelengths the material's magnetic permeability is close to unity, after elimination of the vectors **B** and **H** from equations (1.4), we obtain

$$\partial^2 \mathbf{D}/\partial t^2 + c^2 \operatorname{rot} \operatorname{rot} \mathbf{E} = 0. \tag{1.5}$$

This equation, together with the constitutive equation

$$\mathbf{D} = \varepsilon \mathbf{E} \tag{1.6}$$

describes the space-time variations of the electromagnetic field properties. When dispersion is taken into account, relation (1.6) becomes more complicated and the dielectric constant ε of the medium becomes an operator. However, if waves with reasonably narrow frequency spectrum are examined, the use of the algebraic relation (1.6) is fairly justified within a small frequency interval.

The longitudinal dimensions of light beams in the material are usually much greater than their transversal dimensions. That is why SS, the effectiveness of which drastically depends on the extent of the scattering region, unfolds primarily along the light beam's axis, in the forward or backward direction. To describe the SS process in these conditions, it is convenient to make use of the quasi-optical approximation.

Within the framework of this approximation, the complex amplitude of the electric field of the "input" laser beam

$$E_0 = \mathcal{E}_0 \exp(i\omega_0 t - ik_0 z) + \text{к. с.}, \qquad k_0 = \frac{\omega_0}{c} n(\omega_0). \tag{1.7}$$

is given at one of the material's boundaries (the abbreviation 'c.c.' stands for 'complex conjugate'). At the same (for the forward SS) or the opposite (for the backward SS) boundary is also given the generally non-zero complex amplitude of the electric field of the "scattered" beam