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EDITOR

PROGRESS IN OPTICS

VOLUME XXXV

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PREFACE

This volume contains six review articles on various topics of modern optics and related subjects.

The first article, by N.N. Rosanov, discusses transverse light patterns in nonlinear media, lasers and wide-aperture interferometers. Such patterns may be almost periodic in transverse directions, when they appear as light filaments, or they may be localized, as spatial solitons. They are manifestations of optical "self-organization" and are of interest in connection with information processing.

The second article, by M. Orrit, J. Bernard, R. Brown and B. Lounis, deals with the detection and spectroscopic studies of single molecules in transparent solids at low temperature. The isolated spectral line of a single molecule makes it possible to perform basic quantum measurements, and allows probing in unprecedented detail of the surrounding solid matrix. The article also includes some suggestions for future research in this field.

The article by K. Itoh which follows, reviews interferometric techniques for retrieving multispectral images with a large number of spectral channels. Special attention is paid to the theory of interferometric multispectral imaging which unifies the theories of coherence-based image retrieval and spectrum recovery. Various techniques are compared, especially in terms of signal-to-noise-ratio.

In the fourth article D. Paoletti and G. Schirripa Spagnolo present a review of holographic and electronic speckle interferometric techniques applied to artwork diagnostics. It describes the most important tests performed on models and real artwork.

The next article, by E. Arimondo, discusses coherent population trapping in laser spectroscopy and reviews experiments on the detection and utilization of trapping. The coherent superposition of states, which is an essential part of the phenomenon, arises in laser spectroscopy, optical bistability, four-wave mixing, light-induced drift, laser cooling, adiabatic transfer, lasing without inversion, pulse matching, photon statistics and atomic and molecular ionization. Aspects of the theoretical analysis and of experimental observations are described and discussed with the view to some possible future applications.

The last article, by R. Tanaś, A. Miranowicz and Ts. Gantsog, presents a review of quantum phase properties of optical fields generated in some nonlinear optical processes. Various states of the field, such as coherent states, squeezed states, anharmonic oscillator states and second- and sub-harmonic fields, exhibit different phase properties. Modern formalisms, such as the Pegg–Barnett Hermitian phase formalism and the formalism based on the so-called s-parametrized quasi-distribution functions for example, are used to elucidate such properties in a systematic way.

In view of the wide range of topics discussed in this volume, we hope that most readers will find in this book something that is of interest to them.

Emil Wolf

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I

TRANSVERSE PATTERNS IN WIDE-APERTURE NONLINEAR OPTICAL SYSTEMS

BY

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CONTENTS

§ 1. Introduction

Spontaneous symmetry breaking that results in the formation of light patterns in transversely homogeneous nonlinear optical systems has attracted the attention of investigators for about three decades. These investigations began with radiation self-focusing, including (1) large-scale self-focusing in the form of self-trapping, or spatial solitons, when diffractive spread of the propagating beam is compensated by its focusing with a nonlinear medium (Askar'yan [1962], Chiao, Garmire and Townes [1964], Talanov [1964]); and (2) small-scale self-focusing, or filamentation, that is, instability of nonlinear propagation of a plane wave and its breakup into separate filaments (Bespalov and Talanov [1966]).

Special attention was paid to filamentation, which created a real problem for laser investigators, because the filamentation prevented the increase of radiation brightness in high-power laser systems. As a result, several effective ways of filamentation suppression were proposed and realized (Mak, Soms, Fromsel and Yashin [1990]).

Spatial solitons, for example, in a Kerr medium, were found to be unstable. Temporal solitons in nonlinear optical fibers, mathematically equivalent to 1D (one-dimensional) spatial solitons, were shown to have high application potential, however, and they were thoroughly investigated, both theoretically and experimentally (Hasegawa [1989]).

Recently the situation has changed. Stable spatial transversely 1D solitons were demonstrated in planar waveguides with Kerr optical nonlinearity (Barthelemy, Maneuf and Froehly [1985]). The idea of spatiotemporal solitons ("light bullets") was suggested for a homogeneous medium with self-focusing nonlinearity and anomalous dispersion (Silberberg [1990]). Stable or metastable transversely 2D solitons with wavefront dislocations, or vortices, were demonstrated for a Kerr medium and for a medium with saturable nonlinearity (Kruglov, Volkov, Vlasov and Drits [1987], Swartzlander and Law [1992]). New types of transverse patterns with rather striking features were found in the systems with feedback (wide-aperture nonlinear interferometers, lasers, etc.). Recognition of the optical patterns as a manifestation of self-organization phenomena was useful and instructive. Optical instabilities and filamentation became popular, and nonlinear investigators successfully tried to destabilize increasing numbers of optical systems.

Currently the field of optical transverse patterns is rather broad, and it is impossible to describe all known results in this chapter (see also Abraham and Firth [1990], Rosanov, Mak and Grasiuk [1992], Lugiato [1994], and references therein). I will try to review the main ideas and emphasize some new features of self-organization specific for optics, compared with features typical for other nonlinear physical, chemical, and biological objects (Nicolis and Prigogine [1977], Haken [1978], Cross and Hohenberg [1993]).

The chapter starts with the classical problem of small-scale self-focusing (filamentation, or modulational instability) for one and two plane waves (§ 2.1), partly because of the simplicity and general character of its theory. To answer the question of whether any patterns will arise in the given wide-aperture system, it is useful to check the possibility of filamentation in the corresponding ideal transversely homogeneous system (plane-wave instability). In the case of filamentation, it is clear that radiation in a wide-aperture system will eventually break up into many filaments. Therefore, some transverse patterns have to arise in the system under conditions derived from the simple filamentation approach. A more realistic theory of wide-beam filamentation is given in § 2.2. The chapter then describes surface and guided waves filamentation (§ 2.3). In such systems (i.e., without feedback) instability has a convective character (perturbations grow with a longitudinal coordinate), whereas in the systems with feedback (§ 2.4), instability is absolute (perturbations grow with time).

In § 3 different types of stable filaments, spatial solitons, are described. Their formation and interaction determine the final form of the filamentation in the wide-aperture system. An almost exhaustive description of such phenomena is known for 1D geometry and for a medium with Kerr nonlinearity (§ 3.1). Section 3.2 presents computer simulations of interaction of solitons for transversely 2D schemes, which give some insight into a more complicated picture of nonlinear propagation and interaction of high-power radiation beams. Spatiotemporal solitons ("light bullets") are discussed in § 3.3.

The second part of the review (§ 4–§ 6) examines the essentially different types of spatial patterns that are inherent in systems with feedback. Filamentation instability is not needed for their formation, hence they can be generated only by a sufficiently large initial perturbation. The examples are switching waves (§ 4) and diffractive autosolitons (§ 5). The autosolitons are reviewed mainly for the scheme of a nonlinear interferometer; similar structures are also described for the laser with saturable absorption (§ 6.1) and for the waveguide with saturable amplification and absorption (§ 6.2). They are particle-like field structures with rather striking "quantum" and "mechanical" features. We would like to underline that, contrary to the usual solitons, the diffractive autosolitons have a discrete spectrum of their width. This difference is fundamental, and leads to new physics and possible new applications, which are discussed briefly in the conclusion.

§ 2. Filamentation

In this section we consider the simplest case of nonlinear propagation of radiation. The electromagnetic field is taken to be quasimonochromatic, and its polarization state does not vary significantly. Then the field can be characterized by a scalar complex amplitude $\widetilde{E}$ whose envelope E slowly varies in space (in the scale of light wavelength λ)

$$\widetilde{E}(\boldsymbol{r}_\perp, t) = \tfrac{1}{2}E(\boldsymbol{r}_\perp)\exp[\mathrm{i}(kz - \omega t)] + \text{c.c.}, \tag{2.1}$$

where z is the longitudinal coordinate and $\boldsymbol{r}_\perp = x,y$ is a vector of the transverse coordinates. The isotropic transparent medium is characterized by nonlinear electrical permittivity

$$\varepsilon = \varepsilon_0 + \delta\varepsilon(|E|^2), \qquad \delta\varepsilon(0) = 0.$$

For the Kerr medium $\delta\varepsilon = \varepsilon_2 |E|^2$, where ε_2 is the coefficient of nonlinearity. For resonant nonlinearity (two-level scheme far off the absorption line, $I_\mathrm{s} = |E_\mathrm{s}|$ is intensity of saturation)

$$\delta\varepsilon = \varepsilon_2 \frac{|E|^2}{1 + |E/E_\mathrm{s}|^2}. \tag{2.2}$$

The envelope E obeys the standard paraxial equation

$$2\mathrm{i}k\frac{\partial E}{\partial z} + \Delta_D E + k^2\frac{\delta\varepsilon}{\varepsilon_0}E = 0, \tag{2.3}$$

where Δ_D is the transverse Laplacian ($D = 1$ or 2, depending on the scheme geometry). A plane wave serves as a solution of eq. (2.3)

$$E = E_0 \exp(\mathrm{i}\beta z). \tag{2.4}$$

Here, $E_0 = \text{const.}$, $\beta = k_0\delta\varepsilon(I_0)/2\varepsilon_0$, and $I_0 = |E_0|^2$.