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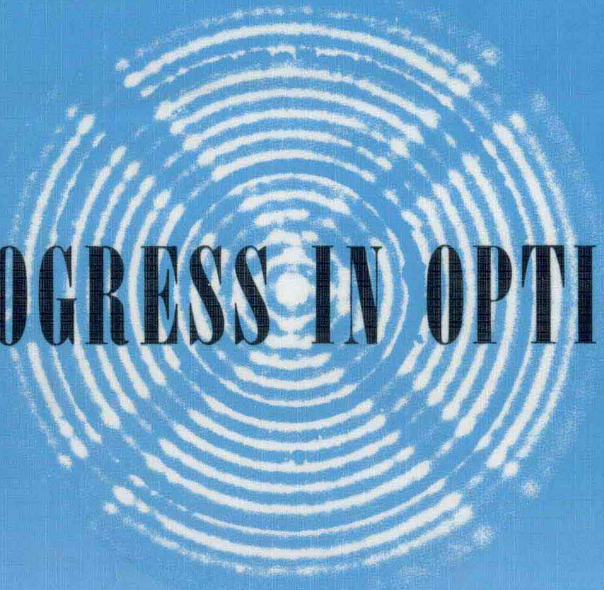

PROGRESS IN OPTICS

VOLUME XXXIX

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1999

ELSEVIER
AMSTERDAM · LAUSANNE · NEW YORK · OXFORD · SHANNON · SINGAPORE · TOKYO

PROGRESS IN OPTICS

VOLUME XXXIX

ELSEVIER SCIENCE B.V.
SARA BURGERHARTSTRAAT 25
P.O. BOX 211
1000 AE AMSTERDAM
THE NETHERLANDS

Library of Congress Catalog Card Number: 61-19297
ISBN Volume XXXIX: 0 444 50104 5

⊗ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

PRINTED IN THE NETHERLANDS

PREFACE

In this volume five review articles are presented dealing with topics of current research interests in optics.

The first article, by Yu.A. Kravtsov, G.W. Forbes and A.A. Asatryan, is concerned with the analytic extension of the concept of geometrical optics rays into the complex domain. The extension is intimately related to inhomogeneous (evanescent) waves, which are currently of particular interest in connection with the rapidly developing area of near-field optics. The results are also relevant to investigations of wave attenuation in absorbing media, and to the understanding of light penetration into geometrical shadow regions, excitation of surface waves and propagation of Gaussian beams. The article presents the principles, with special emphasis on the physical significance of complex rays and their applications.

The second article, by D.-G. Welsch, W. Vogel and T. Opatrný, describes recent progress in the general area of quantum-state reconstruction, particularly for extracting information about the quantum state of a given object from a set of measurements. The methods are applicable to the optical field as well as to various matter waves. Some methods of processing the measured data and many of the important experiments in this area are discussed.

The next article, by S.K. Sharma and D.J. Somerford, is concerned with the scattering of light in the eikonal approximation. This approximation originated in the theory of high-energy scattering processes and in the broad area of potential scattering. From the well-known analogy between a scattering potential and the distribution of the refractive index, the eikonal approximation was later adapted to the analysis of light scattering by small particles. In this article an account is given of the eikonal approximation in the context of optical scattering, and its domain of validity is discussed. The relationship of this approximation to other approximate techniques as well as some of its possible applications are considered.

The fourth article, by L. Allen, M.J. Padgett and M. Babiker, concerns the orbital angular momentum of light. The orbital angular momentum is shown to be an observable quantity which can be profitably used with certain types of light beams. The phenomenological interaction of the beams with matter in bulk is reviewed and the contributions of the orbital angular momentum to the dissipative and dipole forces on atoms are calculated in detail. Orbital and spin angular momentum of light are compared and contrasted.

The concluding article, by A. Sizmann and G. Leuchs, presents a review of the experimental progress made in recent years in the generation of squeezed light and in quantum nondemolition measurements in optical fibers. The rich nonlinear dynamics of quantum solitons in fibers has led to the discovery of new quantum optical effects, such as intrapulse quantum correlations. The nonlinearity of optical fibers is now used to build passive fiber devices which provide all-optical functions, such as quantum noise reduction, and it is expected that active devices will allow absorption-free measurements of optical signals. The review is also concerned with these and other promising developments in this general area.

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December 1998

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I

THEORY AND APPLICATIONS OF COMPLEX RAYS

BY

YU.A. KRAVTSOV[1], G.W. FORBES[2] AND A.A. ASATRYAN[2]

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CONTENTS

§ 1. Introduction

1.1. PIONEERING WORKS

Complex rays are solutions of the ray equations of traditional geometrical optics, but correspond to extremals in the six-dimensional complex space $(x', x'', y', y'', z', z'')$, where $x' = \mathrm{Re}\{x\}$, $x'' = \mathrm{Im}\{x\}$, etc. These trajectories can be used to derive both the phase and amplitude of the associated wavefield. Complex rays were first considered during the 1930s and 1940s in the theory of radio wave propagation through the lossy ionosphere (Epstein [1930a,b], Booker [1939], Bremmer [1949]), but a more general formalization was not developed until the late 1950s and early 1960s. The decisive step in understanding the analytical nature of complex rays was made by Keller [1958], who introduced the notion of complex rays to treat the area of a caustic shadow. He studied the equations for rays passing through points in the interior of a circular caustic in two dimensions and showed that such rays contact the caustic surface at complex points that lie on its analytic continuation.

A year later, Seckler and Keller [1959] studied complex rays in plane-layered media, and Keller and Karal [1960] applied complex rays to the problem of surface wave excitation. Grimshaw [1968] studied these surface waves in more detail for particular surfaces (the sphere, the cone, and the plane with inhomogeneous impedance). Babich [1961] considered the analytic continuation of the wave function into the caustic shadow, and performed calculations that may be interpreted in terms of complex rays. A similar analytic continuation was also applied by Keller and Rubinow [1960] who studied eigenfunctions in both open and closed optical resonators. Complex trajectories are the quantum-mechanical analog of complex rays, and were studied by Maslov [1963] in connection with the quasiclassical asymptotics of solutions to the Schrödinger equation. Complex trajectories appeared there as complex solutions of the classical equations of motion in regions that are inaccessible to classical particles (i.e., areas of tunneling). Maslov [1964] also pointed out that complex rays may form foci and caustics.

The application of complex rays within the theory of radio wave propagation through the lossy ionosphere was resumed by Budden [1961], Sayasov [1962], Budden and Jull [1964], and Jones [1968, 1970]. Generally speaking, in lossy media all rays become complex because the index of refraction, which enters both the eikonal and ray equations, takes complex values. The growing interest in these ideas led to the first review paper on complex rays, written by Kravtsov [1967a], in which the analytic nature of complex trajectories was refined and the notion of a complex focus introduced for a Gaussian beam. The idea of using a complex point source to model a Gaussian beam was considered almost simultaneously by Deschamps [1967, 1968, 1971], Arnaud [1968, 1969b], and Keller and Streifer [1971].

Of note also, in one-dimensional problems the method of phase integrals (see, e.g., Heading [1962]) can be regarded as a precursor to complex geometrical optics; that is, complex ray methods may be viewed as a generalization of the phase integral method for three-dimensional inhomogeneous media. Similarly, the old idea of a complex angle of refraction for the evanescent component in the case of total internal reflection is a clear ancestor of complex geometrical optics. Thus this field has a long history.

1.2. CHARACTER OF WAVEFIELDS DESCRIBED BY COMPLEX GEOMETRICAL OPTICS

In complex geometrical optics the direction of wave propagation is given by the gradient of the real part of the complex phase, and the direction of exponential decay of the field's magnitude is principally determined by the gradient of the imaginary part. In nonabsorbing media these directions are orthogonal, but in lossy media they are separated by an acute angle. In both cases inhomogeneous waves can enter, and their magnitude changes exponentially on a phase front. In fact, just as homogeneous (propagating) waves are the subject of traditional geometrical optics, inhomogeneous (or evanescent) waves can be regarded as the principal subject of complex geometrical optics (Kravtsov [1967a,b], Choudhary and Felsen [1973], Felsen [1976a]).

Like traditional geometrical optics, complex geometrical optics can involve a multiplicity of rays, so that the total wavefield is then a sum of the waves associated with each ray. As emphasized by Kravtsov [1967a,b], when multiple complex rays are present, selection rules are typically required to exclude nonphysical solutions. Another feature of complex rays is that, unlike real rays, they can describe nonlocal (diffraction-like) processes. A clear demonstration of their nonlocal properties is provided by the example of Gaussian beams, see § 5. It is shown in that section that complex geometrical optics provides a complete description of a Gaussian beam (Kravtsov [1967a,b], Keller and Streifer [1971]).