

A
monthly
journal

Applied Physics

Board of Editors

S. Amelinckx, Mol. V.P. Chebotayev, Novosibirsk
R. Gomer, Chicago, IL., H. Ibach, Jülich
V.S. Letokhov, Moskau, H.K.V. Lotsch, Heidelberg
H.J. Queisser, Stuttgart, F.P. Schäfer, Göttingen
A. Seeger, Stuttgart, K. Shimoda, Tokyo
T. Tamir, Brooklyn, NY, W.T. Welford, London
H.P.J. Wijn, Eindhoven

Coverage

application-oriented experimental and theoretical physics:

<i>Solid-State Physics</i>	<i>Quantum Electronics</i>
<i>Surface Sciences</i>	<i>Laser Spectroscopy</i>
<i>Solar Energy Physics</i>	<i>Photophysical Chemistry</i>
<i>Microwave Acoustics</i>	<i>Optical Physics</i>
<i>Electrophysics</i>	<i>Integrated Optics</i>

Special Features

rapid publication (3-4 months)
no page charge for **concise** reports
prepublication of titles and abstracts
microfiche edition available as well

Languages
mostly English

Articles

original reports, and short communications review
and/or tutorial papers

Manuscripts

to Springer-Verlag (Attn. H. Lotsch), P.O. Box 105 280
D-6900 Heidelberg 1, F.R. Germany

Place North-American orders with:
Springer-Verlag New York Inc., 175 Fifth Avenue,
New York, N.Y. 100 10, USA



Springer-Verlag
Berlin
Heidelberg
New York

Topics in Applied Physics Volume 25



Topics in Applied Physics

Founded by Helmut K. V. Lotsch

- Vol. 1 **Dye Lasers** 2nd Edition Editor: F. P. Schäfer
 - Vol. 2 **Laser Spectroscopy of Atoms and Molecules** Editor: H. Walther
 - Vol. 3 **Numerical and Asymptotic Techniques in Electromagnetics** Editor: R. Mitra
 - Vol. 4 **Interactions on Metal Surfaces** Editor: R. Gomer
 - Vol. 5 **Mössbauer Spectroscopy** Editor: U. Gonser
 - Vol. 6 **Picture Processing and Digital Filtering** Editor: T. S. Huang
 - Vol. 7 **Integrated Optics** Editor: T. Tamir
 - Vol. 8 **Light Scattering in Solids** Editor: M. Cardona
 - Vol. 9 **Laser Speckle and Related Phenomena** Editor: J. C. Dainty
 - Vol. 10 **Transient Electromagnetic Fields** Editor: L. B. Felsen
 - Vol. 11 **Digital Picture Analysis** Editor: A. Rosenfeld
 - Vol. 12 **Turbulence** 2nd Edition Editor: P. Bradshaw
 - Vol. 13 **High-Resolution Laser Spectroscopy** Editor: K. Shimoda
 - Vol. 14 **Laser Monitoring of the Atmosphere** Editor: E. D. Hinkley
 - Vol. 15 **Radiationless Processes in Molecules and Condensed Phases** Editor: F. K. Fong
 - Vol. 16 **Nonlinear Infrared Generation** Editor: Y.-R. Shen
 - Vol. 17 **Electroluminescence** Editor: J. I. Pankove
 - Vol. 18 **Ultrashort Light Pulses. Picosecond Techniques and Applications**
Editor: S. L. Shapiro
 - Vol. 19 **Optical and Infrared Detectors** Editor: R. J. Keyes
 - Vol. 20 **Holographic Recording Materials** Editor: H. M. Smith
 - Vol. 21 **Solid Electrolytes** Editor: S. Geller
 - Vol. 22 **X-Ray Optics. Applications to Solids** Editor: H.-J. Queisser
 - Vol. 23 **Optical Data Processing. Applications** Editor: D. Casasent
 - Vol. 24 **Acoustic Surface Waves** Editor: A. A. Oliner
 - Vol. 25 **Laser Beam Propagation in the Atmosphere** Editor: J. W. Strohbehn
 - Vol. 26 **Photoemission in Solids I. General Principles** Editors: M. Cardona and L. Ley
 - Vol. 27 **Photoemission in Solids II. Case Studies** Editors: L. Ley and M. Cardona
 - Vol. 28 **Hydrogen in Metals I. Basic Properties** Editors: G. Alefeld and J. Völkl
 - Vol. 29 **Hydrogen in Metals II. Application-Oriented Properties**
Editors: G. Alefeld and J. Völkl
 - Vol. 30 **Excimer Lasers** Editor: C. K. Rhodes
 - Vol. 31 **Solar Energy Conversion. Solid-State Physics Aspects** Editor: B. O. Seraphin
 - Vol. 32 **Image Reconstruction from Projections. Implementation and Applications**
Editor: G. T. Herman
-

Laser Beam Propagation in the Atmosphere

Edited by J. W. Strohbehm

With Contributions by

S.F.Clifford M.E.Gracheva A.S.Gurvich A.Ishimaru
S.S.Kashkarov V.V.Pokasov J.H.Shapiro
J.W.Strohbehm P.B.Ulrich J.L.Walsh

With 78 Figures

Springer-Verlag Berlin Heidelberg New York 1978

Professor *John W. Strohbehn*

Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, USA

ISBN 3-540-08812-1 Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-08812-1 Springer-Verlag New York Heidelberg Berlin

Library of Congress Cataloging in Publication Data. Main entry under title: Laser beam propagation in the atmosphere. (Topics in applied physics; v. 25). Bibliography: p. Includes index. 1. Laser beams-Atmospheric effects. 2. Atmosphere - Laser observations. 3. Atmospheric turbulence. I. Strohbehn, J. W., 1936-. II. Clifford, Steven Francis, 1943-. QC976.L36L37 551.5'27 78-19100

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically those of translation, reprinting, re-use of illustrations, broadcasting, reproduction by photocopying machine or similar means, and storage in data banks. Under §54 of the German Copyright Law, where copies are made for other than private use, a fee is payable to the publisher, the amount of the fee to be determined by agreement with the publisher.

© by Springer-Verlag Berlin Heidelberg 1978
Printed in Germany

The use of registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Monophoto typesetting, offset printing and bookbinding: Brühlsche Universitätsdruckerei, Lahn-Giessen
2153/3130-543210

Preface

When optical waves, whether they originate from starlight, incandescent sources, or lasers, propagate through the clear atmosphere of the earth, they experience distortions due to small temperature variations. The two most common manifestations of this phenomena are the twinkling of stars and the shimmering of "heat" over hot pavement or surfaces. The small temperature variations, on the order of 1°C or less, are related to the sun's heating of the atmosphere and turbulent motion of the air due to winds and convection. The small temperature perturbations cause changes in the velocity of the light as it passes through the atmosphere, which in turn causes distortions in the intensity (twinkling), phase, angle-of-arrival, and displacement (quivering) of the light beam.

With the invention of the laser in 1962 and the myriad of possible practical applications, from lidar (laser radars) to communications, interest in atmospheric effects on optical waves rapidly expanded. In this volume we attempt to cover the latest developments in this field. Earlier monographs on this subject include those of Chernov (*Wave Propagation in a Random Medium*) and Tatarskii (*Wave Propagation in a Turbulent Medium, and the Effects of the Turbulent Atmosphere on Wave Propagation*). The emphasis in this volume is on situations where temperature variations in the atmosphere dominate the laser propagation characteristics. Most of the volume is concerned with problems dominated by the earth's atmospheric turbulence, except for the last chapter which considers the case where the laser beam itself is so powerful that it produces the heating of the atmosphere. This volume does not consider effects on laser beams caused by absorption of the light energy by molecules or particles nor does it consider scattering of the light by aerosols or rain or fog.

The first chapter is an introduction and attempts to provide an overview of the subject and the material included in this volume. The second chapter, by S. F. Clifford, presents the classical theory of optical propagation through a turbulent atmosphere including a description of the atmospheric model. This chapter represents the state of the art of the theory until the middle 1960's and is applicable for a wide range of practical problems. The next chapter, by J. W. Strohbehn, attempts to summarize and compare the modern approaches to laser propagation through the turbulent atmosphere, with particular attention to the region where the classical theory has been shown not to be valid. This theory is necessary for laser propagation over long paths and when the strength of the refractive index turbulence is high. Chapter 4 describes the results of a very thorough set of measurements, performed by M. E. Gracheva et al. in 1972,

on laser signals in the region where the classical theory breaks down. While the theory in the chapters by Clifford and Strohbehn assumes the initial wave is plane or spherical, Chapter 5, by A. Ishimaru, concentrates on the subtleties of the theory presented by finite-size laser beams which may or may not be focused. This chapter also introduces the problem of using measurements of laser signals to remotely probe atmospheric characteristics such as the strength of the turbulence or the velocity of the wind. J. Shapiro, in Chapter 6, addresses the communications and imaging problems when an optical signal passes through the turbulent atmosphere. Based on the results of the preceding chapters he defines the optimum receiver for communications and analyzes the receiver's performance. Finally, in the last chapter, J. Walsh and P. Ulrich consider the problem known as thermal blooming. In this situation, the intensity of the laser beam is so great that it heats the atmosphere through which it passes. The heated atmosphere distorts the original laser beam so that the beam size is expanded (blooming) and, in the presence of a wind, displaces the position of the beam. These authors give one of the first thorough reviews of this interesting topic.

It is my pleasure to acknowledge some of the debts I have incurred and the inspiration I have received. In particular, I would like to thank A. Waterman, Jr. who got me started on radio-wave propagation, V. I. Tatarskii with whom I had many interesting discussions on the modern theories of laser propagation, and M. G. Morgan who provided an ideal environment in which to work. Besides the contributors, discussions with R. Lawrence, W. P. Brown, D. Fried, R. Fante, and H. Yura materially influenced the direction of this volume. The authors who wrote most of the text have worked hard and patiently to produce high quality manuscripts. Dean C. F. Long generously provided the time and support necessary for the writing and editing of this volume. Janet Brown quickly and accurately typed my contributions as well as Chapter 7, and Cutting Johnson did a superb job with the figures in Chapter 3, 4, and 7. Finally, a special thanks to my children, Jo, Kris, and Carolyn, for cheerfully enduring the many extra hours and late meals while this project was underway—it is to them that my efforts are dedicated.

Hanover, New Hampshire
July, 1978

J. W. Strohbehn

Contents

1. Introduction. Laser Beam Propagation in the Atmosphere	
By J. W. Strohbehn	1
1.1 A Brief History	3
1.2 Organization	4
References	6
2. The Classical Theory of Wave Propagation in a Turbulent Medium	
By S. F. Clifford (With 9 Figures).	9
2.1 Description of the Atmosphere	10
2.1.1 Atmospheric Refractive Index	10
2.1.2 The Role of Atmospheric Turbulence	11
2.1.3 The Turbulence Model of Refractivity Fluctuations	12
2.1.4 Stationary Random Functions	14
2.1.5 The Power Spectral Density of the Refractive Index Fluctuations	16
2.1.6 Behavior of C_n^2 in the Open Atmosphere	20
2.2 The "Classical" Theory of Optical Propagation	26
2.2.1 The Wave Equation for Optical Propagation	26
2.2.2 Solution by the Method of Small Perturbations	27
2.2.3 Covariance and Structure Functions for Kolmogorov Turbulence	34
2.2.4 A Qualitative Interpretation of the First-Order Scattering Theory	37
2.3 The Early Experimental Work	39
References	41
3. Modern Theories in the Propagation of Optical Waves in a Turbulent Medium. By J. W. Strohbehn (With 18 Figures)	45
3.1 Overview	45
3.2 The Diagram Method	52
3.3 The Markov Approximation	59
3.3.1 The Derivation for the Mean Field	60
3.3.2 The Derivation for the Mutual Coherence Function	62
3.3.3 The Derivation of Higher Order Moments	64
3.4 The Local Method of Small Perturbations (LMSP)	67
3.5 Heuristic Theories for the Saturation Region	70

3.6 Results	83
3.6.1 The Mean Field, $u(r)$	84
3.6.2 The Mutual Coherence Function	85
3.6.3 The Fourth-Order Coherence Function	86
3.6.4 The Probability Distribution of the Irradiance	97
References	104
4. Similarity Relations and Their Experimental Verification for Strong Intensity Fluctuations of Laser Radiation. By M. E. Gracheva, A. S. Gurvich, S. S. Kashkarov, and Vl. V. Pokasov Translated and adapted by J. W. Strohbehn (With 13 Figures)	107
4.1 Background	107
4.2 Derivation of the Similarity Formulas	108
4.2.1 The Fourth-Order Coherence Function	108
4.2.2 The Similarity Relations	109
4.2.3 Physical Meaning of L_T and I_T	109
4.2.4 Comparison with Experiment	110
4.2.5 Similarity Relations for the Probability Distribution and Moments	111
4.2.6 Limitations in Comparing Theory and Experiment	112
4.3 The Experimental Plan and Measurement Procedures	112
4.4 Experimental Results and Their Discussion	114
4.4.1 The Log Normal <i>vs</i> Rayleigh Probability Distribution	114
4.4.2 The Dependence of the Probability Distribution on β_0^2	116
4.4.3 The Normalized Variance β^2	116
4.4.4 The Normalized Covariance Function	119
4.4.5 Spectral Measurements	122
4.5 Conclusions	126
References	126
5. The Beam Wave Case and Remote Sensing By A. Ishimaru (With 8 Figures)	129
5.1 Weak Fluctuation Theory	132
5.1.1 The Variance of the Log Amplitude Fluctuations	134
5.1.2 Average Intensity and Beam Spread	136
5.1.3 Angle of Arrival	140
5.1.4 Temporal Frequency Spectra	140
5.2 Strong Fluctuation Theory	141
5.2.1 Strong Fluctuation Theory for the Coherence Function	142
5.2.2 Temporal Frequency Spectra	151
5.2.3 Two-Frequency Correlation Function	152
5.2.4 Fourth-Order Moments	153
5.2.5 Short- and Long-Term Beam Spreads	154

5.3	Optical Remote Sensing	156
5.3.1	Remote Sensing of the Average Structure Constant C_n Over the Path	156
5.3.2	Remote Sensing of the Average Wind Velocity Across the Path	157
	Temporal Frequency Spectrum Method	158
	Time Delay Method	161
	Correlation Slope Method	162
5.3.3	Remote Sensing of the Profile of the Structure Constant and Wind Velocity Along the Propagation Path	162
	Least Square Estimation	163
	Statistical Inversion Method	165
	Backus-Gilbert Inversion Technique	167
5.3.4	Other Remote Sensing Techniques	168
	Crossed Beam Method	168
	Spatially Filtered Aperture Technique	168
	References	168
6.	Imaging and Optical Communication Through Atmospheric Turbulence	
	By J. H. Shapiro (With 15 Figures)	171
6.1	Propagation Model	172
6.1.1	Extended Huygens-Fresnel Principle	173
6.1.2	Green's Function Statistics	177
6.1.3	Normal Mode Decomposition	180
6.2	Imaging Applications	183
6.2.1	Propagation Model for Incoherent Sources	183
6.2.2	Thin-Lens Imaging	185
6.2.3	Interferometric Imaging	188
6.2.4	Phase-Compensated Imaging	193
6.2.5	Modal Theory of Optimum Imaging	196
6.3	Communication Applications	198
6.3.1	Earth-Space Propagation Channel	199
6.3.2	Statistical Models for Optical Detection	202
6.3.3	Diffraction-Limited Reception	205
6.3.4	Diversity Reception	213
6.3.5	Reciprocity Pointing	217
	References	219
7.	Thermal Blooming in the Atmosphere	
	By J. L. Walsh and P. B. Ulrich (With 15 Figures).	223
7.1	An Overview	224
7.1.1	An Order of Magnitude Estimate	224
7.1.2	Overview of Our Treatment of Thermal Blooming	227
7.1.3	Architecture of Thermal Blooming	228
	Initial Parameters and Method of Approach	228
	Nature of the Resulting Solutions	229

7.2	Electromagnetic Theory	230
7.2.1	The Electromagnetic Wave Equation	230
7.2.2	Scalar Wave Equation for Paraxial Beams	232
7.2.3	Gaussian Beam Modes in a Uniform Medium	233
7.2.4	Geometric Optics	235
7.2.5	Scalar Diffraction Theory in a Uniform Medium	236
7.2.6	Pasted Phase Approximation	239
7.3	Fluid Mechanics	244
7.3.1	Partial Differential Equation for the Density	
	Variations in an Ideal Gas	245
	Stationary Medium	245
	Uniformly Flowing Medium	246
7.3.2	Methods of Solution for the Density	247
	Taylor Expansion for Early Time Behavior	248
	Late Time Behavior	250
	Uniform Transverse Flow at Late Times	250
7.3.3	Formal Solution for a One-Dimensional Heating Profile.	251
	Steady Heating Turned on at $t=0$	251
	Heating with a Multiplicative Time Dependence	253
7.3.4	Formal Solutions for Heating in a Cylindrical Geometry	256
	Hankel Transform Solution for the Uniform Beam	
	Turned on at $t=0$	256
	Green's Function for the Uniform Beam Turned on at $t=0$	257
7.3.5	Representative Solutions in a Slab Geometry	258
	Parabolic Slab in a Transverse Flow	258
	Gaussian Beam Turned on at $t=0$	259
	Uniform Slab Turned on at $t=0$	259
	Parabolic Slab Turned on at $t=0$	262
7.3.6	Representative Solutions in a Cylindrical Geometry.	264
	Gaussian Beam-Early Time	264
	Gaussian Beam in a Transverse Flow	265
	Gaussian Beam Turned on at $t=0$	265
	Uniform Beam of Radius a Turned on at $t=0$	267
	Parabolic Heating Profile Turned on at $t=0$	268
7.3.7	Repetitive Pulses	270
7.3.8	Absorption with a Time Delay in Transfer to	
	Kinetic Energy	271
7.3.9	Electrostrictive Effects	273
7.4	Approximate Analytical Solutions.	276
7.4.1	General Solutions in the Geometric Optics Approximation	277
	Ray Trajectories for Paraxial Beams	277
	Intensity Variation Along the Rays.	278
7.4.2	Example of a Gaussian Slab.	280
7.4.3	Intensity Variation for Collimated Beams	283

7.4.4 Geometric Optics Treatment of Focused Gaussian Beams	284
Case of Steady Heating	286
Early Time Dependence	287
7.4.5 Wave Optics Perturbation Theory	288
Basic Formulation	288
Application to a Gaussian Beam	289
7.4.6 Pasted Phase Approximation	291
7.5 Methodology for Computer Solution of Blooming Problems	294
7.5.1 Numerical Techniques	295
Explicit Algorithm	298
Implicit Algorithm	299
Combined Implicit and Explicit	301
Fast-Fourier Transform Solutions	301
Integral Methods	303
7.5.2 Improvement of Computational Efficiency	303
Nonadaptive Coordinate System	304
Removal of the Nonlinear Phase	306
Adaptive Coordinate Systems	307
7.5.3 Computer Results	308
Early Time Regime	308
Transient Regime	309
Multiple Pulses	312
Steady-State Regime	314
Appendix: Properties of Integral Transforms	316
A.1 Fourier Transforms	316
A.2 Hankel Transforms	317
References	318
Subject Index	321

Contributors

Clifford, Steven F.

Wave Propagation Laboratory, Environmental Research Laboratories,
National Oceanic and Atmospheric Administration,
Boulder, CO 80302, USA

Gracheva, M. E.

Institute of Atmospheric Physics, Pyzhevskii Per 3, Moscow ZH-17, USSR

Gurvich, A. S.

Institute of Atmospheric Physics, Pyzhevskii Per 3, Moscow ZH-17, USSR

Ishimaru, Akira

Department of Electrical Engineering, University of Washington,
Seattle, WA 98195, USA

Kashkarov, S. S.

Institute of Atmospheric Physics, Pyzhevskii Per 3, Moscow ZH-17, USSR

Pokasov, Vl. V.

Institute of Atmospheric Physics, Pyzhevskii Per 3, Moscow ZH-17, USSR

Shapiro, Jeffrey H.

Department of Electrical Engineering and Computer Science, and
Research Laboratory of Electronics, Massachusetts Institute of Technology,
Cambridge, MA 02139, USA

Strohbehn, John W.

Thayer School of Engineering, Dartmouth College,
Hanover, NH 03755, USA

Ulrich, Peter B.

Naval Research Laboratories, Washington, DC 20375, USA

Walsh, John L.

Naval Research Laboratories, Washington, DC 20375, USA